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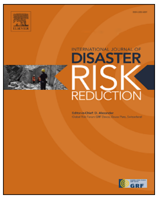

Participatory risk assessment of pluvial floods in four towns of Niger

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ABSTRACT

Intense rainfalls in Sub-Saharan Africa are increasing in frequency. Land degradation, watercourses siltation, and flood defence failure turn these events into disastrous floods. Over the last decade flood risk assessments have been prepared to face these disasters. However, they have frequent limitations in design, accuracy, and completeness. The objectives of this study are (i) to integrate local and scientific knowledge into a participated pluvial flood risk assessment (ii) to identify assets and (iii) to estimate the potential impact and efficiency of risk-reduction measures. The assessment is developed in four rapidly expanding towns of Niger, flooded several times in recent years. Flood-prone areas and assets are identified according four flood scenarios using local knowledge, 2D hydraulic modelling, and visual photointerpretation of very-high-resolution satellite images. Risk-reduction measures are singled-out through public participation. The residual risk and benefit/cost analyses provide a decision-making tool to accept or treat risk. During the last decade the expansion of the four towns has been more rapid in flood-prone zones than in safe areas. Nowadays more than half of the housing stock could be flooded by rainfalls with 20 years return period. Catchment treatment and building retrofitting can reduce risk. from 100 to 29–82. Nevertheless, the benefit/cost of risk reduction is high for towns settled in small catchments only.

1. Introduction

In the last 40 years, floods have affected 80 million people in sub-Saharan Africa [1]. More intense rainfalls [2–6] caused by atmospheric circulation and rising ocean surface temperatures [7], together with soil degradation, have increased flood damages [8,9]. Other factors influencing this problem include the siltation of watercourses [10], soil moisture [11], and failure of flood defences [12]. Additionally, 18% of urban areas in sub-Saharan Africa are located in floodplains [13]. Moreover, the buildings in these areas

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Abbreviations: B, current baseline condition; FRA, flood risk assessment; PD, potential damage; R, risk; RP, return period; T, risk treatment.

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are typically built using non-durable materials [14]. Although asset exposure to flooding is a disaster driver [15], it has not been extensively investigated [16]. The United Nations Sendai Framework for Disaster Risk Reduction encourages member countries to extend their risk knowledge on a local scale [17]. In sub-Saharan Africa, flood-prone zones remain roughly mapped, 70% of cases are not validated, and asset identification is uncommon (Table A1 in Appendix A). Undetailed mapping [18], hampers risk reduction; therefore, the first research problem is mapping flood-prone assets in towns characterised by scarce information and resources.

Flood risk assessments (FRAs) in sub-Saharan Africa typically identify generic risk-reduction measures only (Table A2). Consequently, the residual risk and benefit/cost ratio of risk-reduction [19] cannot be assessed. This information is essential for the decision-making regarding the treatment or acceptance of risks [20]. Therefore, the second research problem is identifying risk-reduction measures accurately.

The literature reports that smaller settlements suffer more flood damage than larger settlements [21–23]. The third research problem relates to the risk reduction efficiency according to settlement size.

Three-quarters of FRAs are conceived and developed using a top-down approach, limiting risk knowledge and ownership of results by local communities (Table A1). Moreover, public participation has been investigated more in risk management [24] than in the evaluation, decision-making [25], and integration of local and scientific knowledge [26]. Thus, the fourth research problem relates to integrating public participation and local knowledge within the ISO 31010 risk-assessment framework [20].

This study aimed to co-develop pluvial FRA with local communities, identify assets and risk-reduction measures, and estimate their potential impact. We used a multidisciplinary approach integrating citizen science, climatology, geomatics, hydraulics, hydrology, and urban planning. We hypothesise that public participation and knowledge integration into FRAs will identify appropriate risk-reduction measures for individual communities and contribute to decision-making.

This study is novel in accurately identifying assets and risk treatment, integrating local knowledge into all stages of FRA according a participatory process, and in its suggested policy implications.

2. Study sites

FRAs were developed in four towns belonging to those more severely affected by flooding in the Dosso region of Niger [27]. Guecheme and Tessa are located in the Maouri and Fogha valleys, respectively, and are the capital towns of the homonymous municipalities. Sabon Birni and Gagila are two small towns in the rural municipalities of Tounouga and Kieche, respectively, located in the Maouri Valley (Fig. 1).

According to the National Population Census (2012) [28], Guecheme, Tessa, Sabon Birni, and Gagila have 8412, 5000, 5970, and 1740 inhabitants, respectively. These towns are located at a slightly higher position than the floodplain. Therefore, they are only exposed to the impact of intense rainfall on the roofs of buildings and the runoff generated in their ungauged catchments. Stream flow is intermittent and linked to intense precipitations typically concentrated in July and August. Guecheme, Gagila, and Sabon Birni lie in small catchments (6, 9, and 12 km^2 respectively). By contrast, Tessa lies in catchments exceeding 21 km^2 (Fig. 2). These towns are only equipped with manual pluviometers characterised by daily time series with lengths between 17 and 38 years [29].

Guecheme and Tessa expanded along a regular unpaved road network on an almost-flat site with some micro-depressions. Except for one street in Guecheme, there were no stormwater drains in the four towns. However, Gagila and Sabon Birni expanded with the addition of irregularly shaped lots along irregular road networks.

In recent years, the frequency of intense rainfall has increased. Runoff has increased following to the conversion of forest and shrubland to range and agricultural land to cater to a growing population and demand for more fuel-wood, meat, cowpea, millet, and sorghum crops. Consequently, runoff increased in many areas of Niger [30,31] and elsewhere in sub-Saharan Africa [32]. Some runoff drivers were specific to individual towns. For example, in Guecheme and Tessa, expansion through land subdivisions along straight roads in the direction of the largest slope exposes these towns to runoff from the catchment. This runoff strikes houses, barns, latrines, warehouses, schools, and wells. Moreover, it can cause temporary isolation (Guecheme), interruption of school attendance, and diseases (Sabon Birni). This is because many assets in flood-prone areas are unprotected, the houses have earthen roofs, walls are made from adobe bricks covered with earthen plaster, and entrance doors have no thresholds. Additionally, the barns are insufficiently high above the ground and were built from crude earth with earthen roofs. The wells and latrines were also unelevated (Fig. 3).

Pluvial floods damaged buildings and infrastructure in two of the four towns more than once a decade (Table A3).

3. Material and methods

The methodology is summarised with respect to the detailed description provided by the authors in a previous study [29]. Risk is "a combination of the consequences of an event and the associated likelihood of occurrence" [32]. For disaster risk, consequences or impacts can be expressed in terms of loss of life, injury, and damage [33]. Therefore, many studies consider risk as the probability of damage [34,35]. Disaster damages are usually expressed in monetary terms [36]. This facilitates residual risk and benefit/cost analyses with respect to the risk equations based on hazard, exposure, vulnerability, and adaptive capacity determinants. In this assessment, risk (R) is the product of the hazard (H) and potential damage (PD). H is the probability that a rainy day will causes damage. In the four towns, daily rainfall with 3-year and 20-years (RP3 and RP20, respectively) return periods were considered. Longer return periods were excluded, because they would involve events that flooded entire towns and exceeded the lifetime of involved assets. PD is the substitution costs for houses, latrines, barns, schools, and warehouses in flood-prone areas.

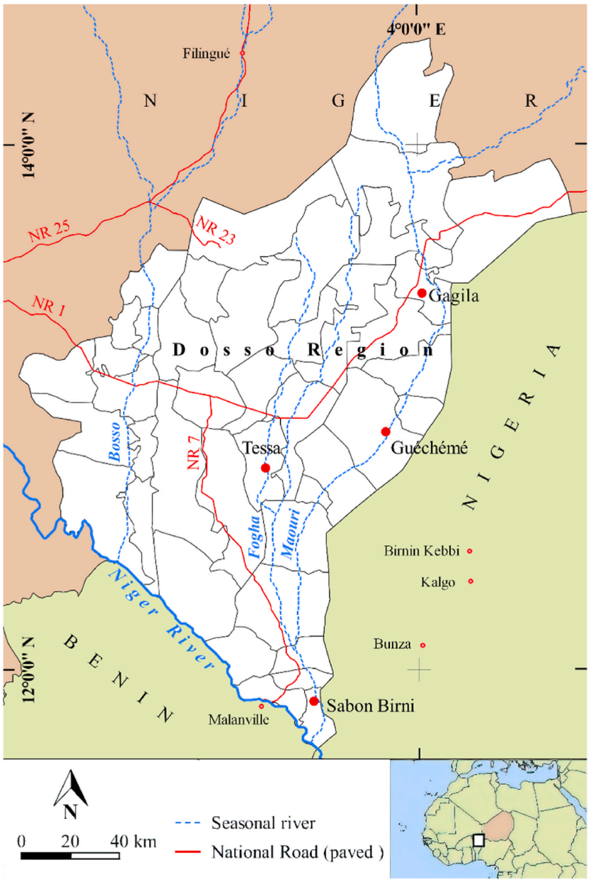


Fig. 1. Four test sites in the Dosso region of Niger.

3.1. *Flood prone areas and assets*

Various methods have been used to determine flood zones, such as indices [37], satellite observations of flooded areas [38], and modelling. This study used hydraulic modelling because it allows the residual risk and the risk treatment efficiency to be estimated according to different scenarios.

The analysis begins with identifying the daily precipitation that triggers damage (critical rainfall). The damage caused by events occurring over the last 20 years, as recorded in the open-access database of floods in Niger (BDINA) [39], was compared with the amount of daily precipitation observed at the rain gauge of each town (Table 1).

Recent trends in critical rainfall levels, flood drivers, and impacts have been determinated through meetings with technicians, local administrators, residents, and inspections in the catchments.

Four return periods (3, 20, 50, and 100 years) were analysed by applying the extreme value theory to the maximal daily rainfall for each year. Four probability distribution functions were tested (generalised extreme value, Gumbel, exponential, and log-normal), and fitting tests (Pearson and Anderson–Darling) were used to select the best distribution [40]. The longer rainfall time series (Guecheme and Sabon Birni) had the best performance with the generalised extreme value probability distribution. By contrast, the shorter ones (Tessa and Gagila) best reflected the Gumbel distribution [41].

The estimation of flood-prone zones involves hydrological and hydraulic analysis. The dimensionless runoff coefficient (Rc) was calculated using the Soil and Water Assessment Tool (SWAT) software [42,43]. The SWAT is a continuous and deterministic hydrological model at the catchment scale, developed by the Agricultural Research Service of the United States Department of Agriculture. Because the investigated catchments were ungauged, calibration and validation of the related SWAT models were impossible; therefore, a regionalisation approach [44] was implemented. This approach implies that the model parameters of similar, but gauged catchments are transferred to ungauged catchments. Spatial proximity assumes that neighbouring catchments have homogenous physical and climatic characteristics; thus, they have similar hydrological responses [45,46]. Therefore, the SWAT model parameters implemented in this assessment were extracted by modelling the Sirba catchment [47], located in South-west Niger.

The Rcs in the current, baseline (B), and catchment post-treatement (T) conditions increased with the length of the return period [48] and decreased with treatments applications [29]. R_C was fundamental determining the net input rainfall and discharge resulting from soil infiltration which could not be evaluated with the hydraulic model.

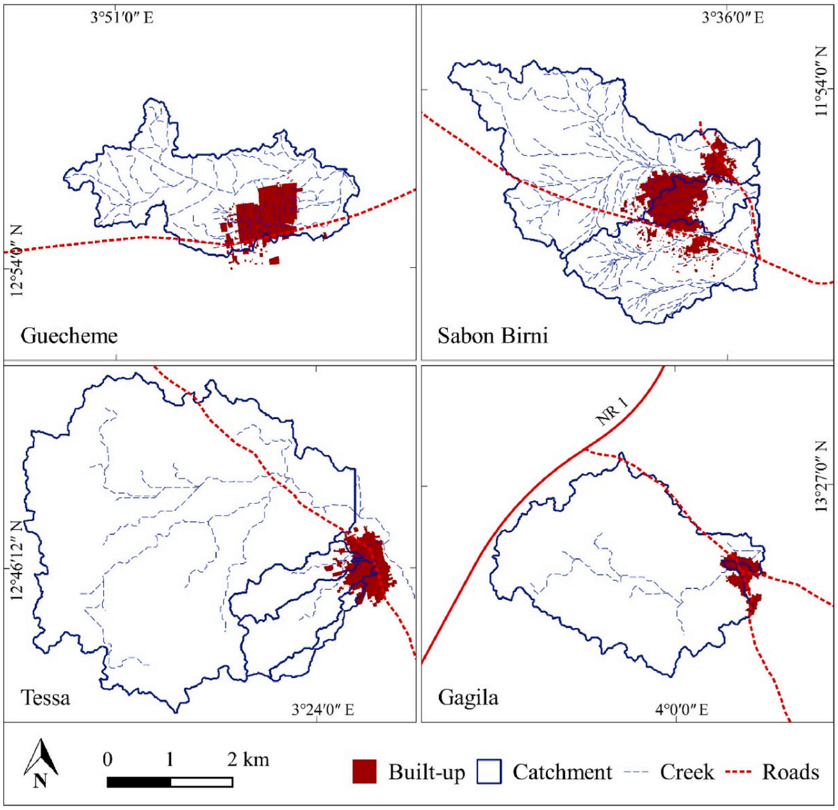


Fig. 2. Catchments in which the four settlements are located.

The hydraulic analysis of the towns was performed using two-dimensional hydraulic models created using the Hydrologic Engineering Centre-River Analysis System software (HEC-RAS) (version 5.0.7) [49]. The flow conditions of the models were simulated by rainfall distributed in the modelled areas and hydrographs concentrated along the primary hydrography. The hyetographs reflect the typical Sahelian storms parameterised by Balme [50] with a symmetrical form and a duration of 1 h. The hydrographs were constructed in a triangular shape with an increasing phase equal to the concentration time (CT) of the basin and a decreasing phase equal to the storm duration. CT was calculated using the Ventura formula $CT = 0.127 \bullet \sqrt{(a/S)}$ where a is the area (km) and S is the adimensional slope of the riverbed. The model geometry was determined using a digital terrain model with a cell size of 10 m (provided by Intermap Technologies Inc.), more accurate than the 30 m currently used by FRAs in sub-Saharan Africa. Soil roughness conditions were defined based on land-cover data [29]. The calibration process included roughness adaptations at the ground and high-resolution satellite imagery to improve the channel shape where the width was finer than a 10 m digital terrain model (DTM) cell. Four simulations were performed for each town according to the 3- and 20-years RPs under the (B) and (T) conditions. Flood-prone zones are the maximum area in which the hydraulic depth exceeds 10 cm, which surpassing the height of the entrance threshold to homes, as observed after systematic field inspections. As in other FRAs in sub-Saharan Africa [51,52], the flood hazard maps were validated with ground control points (GCPs) acquired where the last known floods struck the assets. Twelve to twenty GCPs were completed using a picture, a description of asset materials and use where detected by a local team in each town.

The assets exposed in the RP3 and RP20 flood-prone zones were identified by visual photointerpretation of World View-2 very-high-resolution (VHR) satellite images with a 0.5 m geometric resolution captured on September 1–6, 2019. Each asset measured on the VHR satellite imagery was assigned a replacement value calculated from that of the corresponding standard asset determined in situ. However, barns and latrines were not always identifiable. Therefore, one barn and one latrine were estimated for each flood-prone developed lot. The contents of buildings were not considered in the FRA. The stage-damage curve was redundant for the analysis because the homes were typically built using nondurable materials. These homes collapsed shortly after water intrusion owing to missing thresholds, low thresholds, or earthen roofs.

3.2. Risk reduction measures

In each town, a focus group was established with three distinct categories of participants: mayor and municipal technicians, community women, and community of men. Trapezoidal bunds, half-moons, stone lines (rows of 20–30 cm high stones placed transversely to the slope of the ground), gabions [53], flood maps, corrugated iron roofs, door flood barriers, raised pit latrines, raised wells, and stormwater drains were identified to reduce risk. The areas to be treated with trapezoidal bunds, stone lines, and half-moon soil embankments were identified within the catchments.


Warehouse in durable materials, Gagila
House in durable materials, Tessa


Adobe house, unrised entrance, Gagila
Unraised latrine, Guecheme


Unraised well, Gagila
Unraised fountain, Tessa

Fig. 3. Asset vulnerability in the different towns (photo by M. Tiepolo).

Table 1
Occurrence of critical rainfall over a decade (2010–2019) in the four towns.

Town daily precipitation	Gagila	Guecheme	Sabon Birni	Tessa
mm	69.4	67.5	125	90
Return period, years	3	3	20	5
Date	14/8/2013	15/8/2014	7/8/2012	2/8/2016

3.3. *Residual risk and risk reduction efficiency*

Residual risk (RR) results from the difference between the risk levels before (B) and after treatment (T). The treatement condition (T) was calculated considering the measures to be implemented in the catchment upstream of each town (trapezoidal bunds, half-moons, and stone lines) and within it (protection of buildings with corrugated iron roofs, door flood barriers, and raised latrines). Storm water drains and raised wells were not included in the residual risk estimation. Treating the catchments resulted in a smaller flooding perimeter, as calculated using the hydraulic model. The replacement value of the assets found within the smaller perimeter multiplied by the probability of precipitation with RP3 and RP20 determined the risk of flooding under T condition. The replacement costs of flood-exposed assets with RP3 and RP20 and costs of risk reduction measures are required to assess the RR. The former was determined using information from the local communities (Table A4). The latter was based on the costs of implementing similar measures [54] (Table A5). In the built-up area, the surface area of the earth roofs was determinated to quantify the retrofitting requirements of corrugated iron roofs.

The benefit/cost ratio of the pluvial flood risk reduction was calculated. The benefits were calculated as the difference between the PD under conditions B and T. Costs refers to the expenses incurred by T. The more the benefit/cost ratio exceeded 1, the more the treatment was efficient [19].

3.4. Public participation and local knowledge

Public participation and local knowledge contribute to every step of the FRA. In hazard characterisation, the recent lowering of the critical threshold of daily precipitation beyond which pluvial flooding produces damage was based on local knowledge. According to the hydraulic model, the areas inundated by daily precipitation with RP3 were validated with the georeferenced and photographed inventory of all assets inundated during the 2019 season prepared by a local team in each town. Local knowledge determines the replacement value of flood-prone assets.

Public participation during the two meetings in each town enriches the criteria for selecting measures, identifies the benefits of treating the risk, and decides whether to accept or treat the risk (Fig. 4).

4. Results

4.1. Flood prone area and assets

The mean flow depth in the built-up area ranged between 14–51 cm and 20–61 cm for RP3 and RP20, respectively (Table A6). The flow velocity was typical of a torrential flow and presented very high values, particularly in the hydrological networks of Tessa, Sabon Birni, and Guecheme. The average shares of the towns in the flood-prone zones with RP3 and RP20 were 21% and 32%, respectively. These values reached 54% and 79% after considering the housing stock in the flood-prone zones with RP3 and RP20, respectively [29] (Figs. 5 and 6).

The pluvial flooding risk following rainfall with RP3 varied between €51,000 (Gagila) and €473,000 (Sabon Birni); following rainfall with RP20, the risk varied between €20,000 (Tessa) and €109,000 (Guecheme).

Over the past decade, the built-up areas of the four towns have increased by 43% (Gagila) and 10% (Tessa). Gagila and Guecheme expanded more in the flood-prone zone with RP3, than in the non-flood-prone zone (Table 2). Between 2009 and 2019, the number of homes in the flood-prone zone with RP20, increased by 18–70%, depending on the location (Table 3).

4.2. Risk-reduction measures

As previously discussed, runoff can be reduced and slowed down with trapezoidal bunds, stone lines [55], and half-moons [56] in the catchment area upstream of each town. Protecting the creek banks with gabions is necessary for places where the flow velocity is high (Figs. 7 and 8).

In the flood-prone zones with RP3 and RP20, applying a portable flood barrier at the home entrances and raising barns, wells, and latrines could protect assets. In non-flood-prone built-up areas, corrugated iron roofs should replace earthen roofs. Constructing stormwater drains removes runoff from earthen homes and prevents water stagnation after rainfall (Fig. 9).

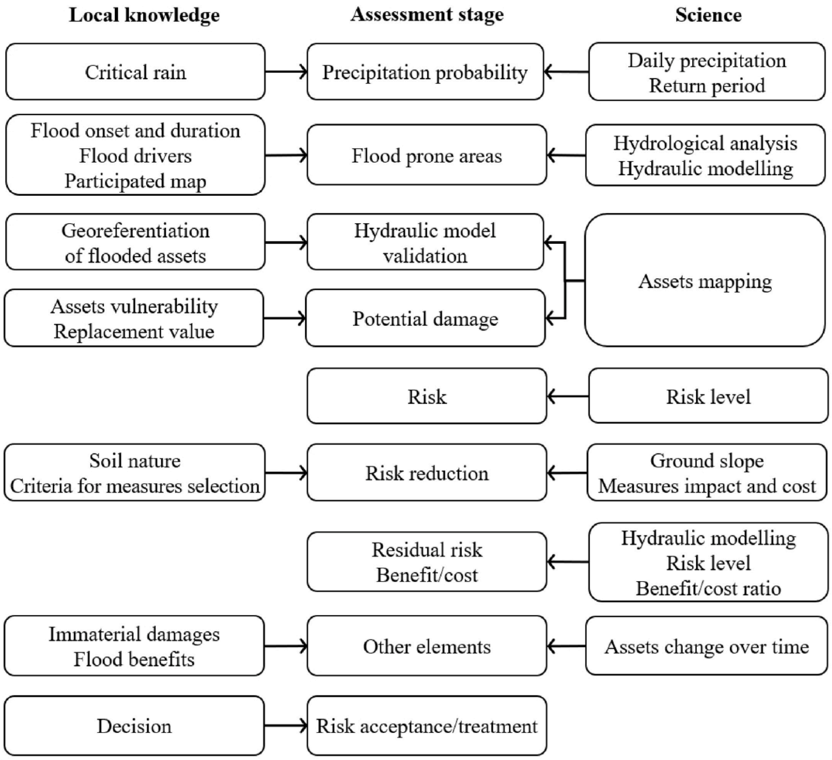


Fig. 4. Integration of local and scientific knowledge into FRA.

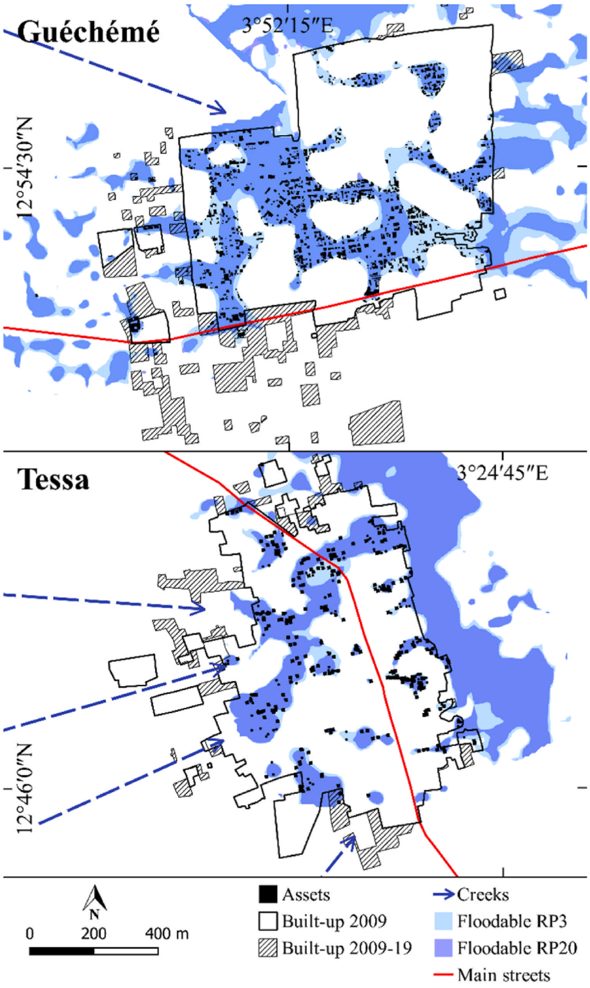


Fig. 5. Guecheme and Tessa hazard maps showing the flood-prone assets.

4.3. *Risk reduction efficiency*

Implementing measures reduced runoff by 10% and 8% for events with RP3 and RP20, respectively. The flood-prone built-up area decreased by 10–24% for RP3 and 21–48% for RP20. The risk level in condition B decreased by 18–71% and 23–49% in the event of rainy days with RP3 and RP20, respectively (Table 4).

The benefit/cost ratio indicated that the measures were efficient in Guecheme for rainfall with RP3, and lower in Tessa for RP20 (0.6) (Table 5).

4.4. *Public participation and local knowledge integration*

The achievements through public participation and local knowledge are extensive. Depending on the town, the daily rainfall amount that can trigger a damage-causing flood ranged 70 and 90 mm. However, this range, has dropped to 50–60 mm in recent years. This information is essential for setting scenarios in the hydraulic model. The georeferentiation of inundated and collapsed assets after last critical rainfall allowed the hydraulic model. Each community identified flood onset, typically occurring at night, and duration. Information on the alteration of the catchment land cover over time owing to crop expansion, deforestation, pastoral pressure resulting from population increase, and vulnerability of assets and their replacement value are further contributions of local knowledge. Communities helped define the criteria for choosing how to treat risk. They emphasized that measures should be known and accepted by the community, feasible with local labour and resources, implemented through mutual aid, require limited maintenance, positively impact the environment, and increase agro-forestry production. Catchment and built-up environment treatment satisfy these criteria.

5. Discussion

Generally, FRAs on a local scale in sub-Saharan Africa rarely identify assets exposed to pluvial flooding and detailed measures to protect them, or co-develop with local communities. Therefore, asset mapping is the first problem when information and resources

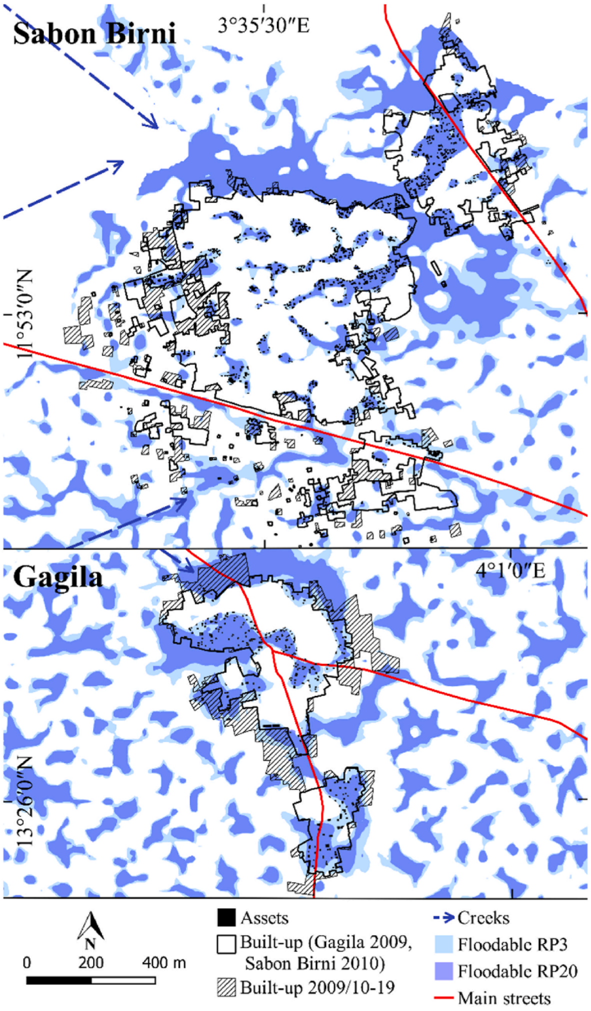


Fig. 6. Sabon Birni and Gagila hazard maps showing the flood-prone assets.

Table 2
Variation of the built-up area in the non-flood-prone and flood-prone areas with RP3 and RP20 between 2009 and 2019 in the four towns.

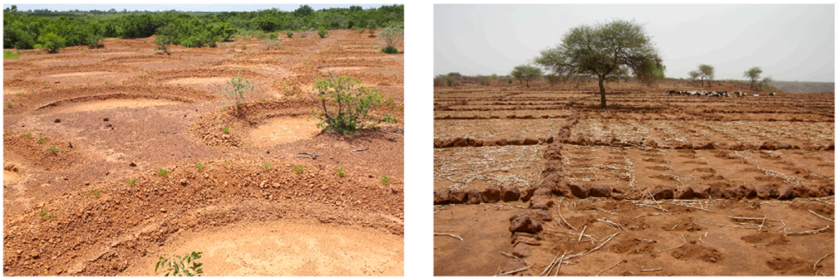
Built-up area	Gagila	Guecheme	Sabon Birni	Tessa
	%	%	%	%
Total	43	20	18	10
Not floodable	46	28	18	13
Floodable RP3	50	45	17	3
Floodable RP20	48	11	0	3

Table 3
Variation of the number of assets between 2009 and 2019 in the RP 20 area.

Asset	Gagila	Guecheme	Sabon Birni	Tessa
	%	%	%	%
Houses	18	29	70	56
Schools	0	33	0	0
Warehouses	0	115	0	0
Barns	−116	−94	−14	−23

Trapezoidal bunds in Keita, Niger

Gabions along a creek in Tessa, Niger



Half-moons in Sabon Birni, Niger

Stone lines in Gahe, Niger

Fig. 7. Trapezoidal bunds, stone lines, half-moons, and gabions (photos by M. Tiepolo).

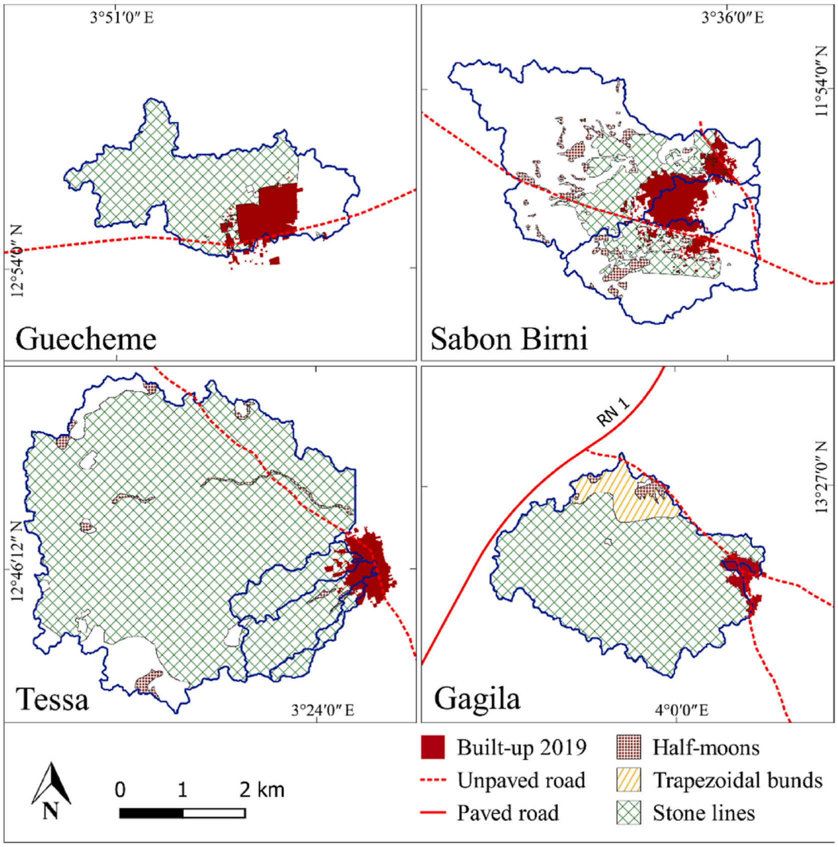


Fig. 8. Localisation of the risk-reduction measures in the catchments of the four towns.

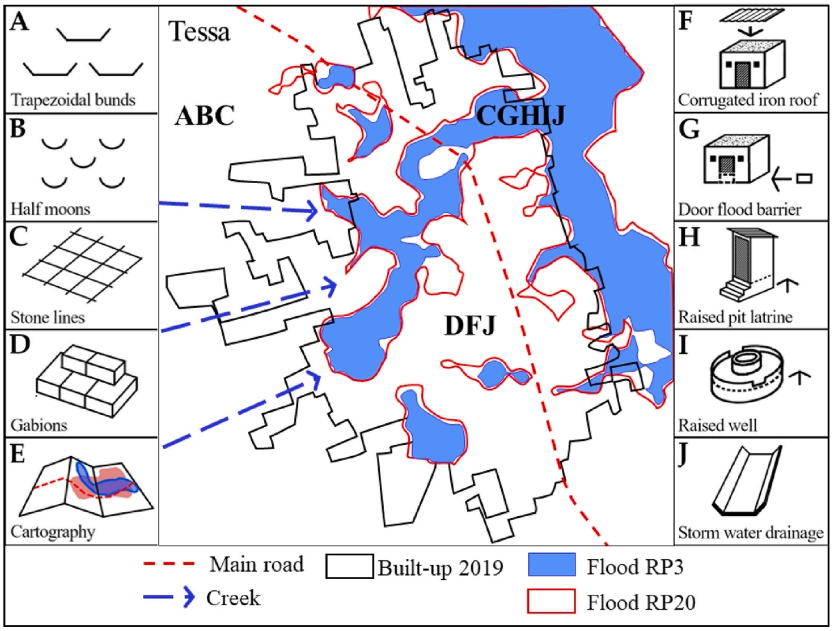


Fig. 9. Ten proposed risk-reduction measures for Tessa town.

Table 4
Risk and residual risk expressed in thousands of Euros (K€) for daily rainfall with RP3 and RP20.

Risk	Gagila	Guecheme	Sabon Birni	Tessa
	K €	K €	K €	K €
B RP3	51	358	473	43
T RP3	35	104	266	36
B RP20	25	109	85	20
T RP20	10	44	65	9

Table 5
Benefit/cost of risk treatement for pluvial flood RP3 and RP20.

RP	Benefit/cost	Gagila	Guecheme	Sabon Birni	Tessa
3	Benefit, K €	444	756	349	629
	Cost, K €	205	104	164	280
	Benefit/cost	2.2	7.3	2.1	2.3
20	Benefit, K €	260	768	274	175
	Cost, K €	183	182	208	280
	Benefit/cost	1.4	4.2	1.3	0.6

are scarce. The second problem is identifying appropriate risk-reduction measures and their potential impact estimations. The third problem focuses on risk reduction efficiency. The fourth problem relates to public participation and local knowledge integration in a risk assessment process already standardised by ISO 31010.

5.1. Mapping the assets exposed to pluvial flood

The four towns extended to 21% in a frequently flooded zone and 32% in a less frequently flooded zone. These values exceeded 18% of the urban surface in flood zone observed in sub-Saharan Africa [13]. The flood-prone zone contained 54% (RP3) to 79% (RP20) of housing stock. The gap between the extension of the flood-prone zone and assets it contains is substantial that FRAs should prefer the latter to calculate the risk level [51,57–59]. This consideration also arises from the observation that, during the last decade, half of the settlements expanded more in the flood-prone zones than in non-flood-prone zones. This dynamic can be explained by a lack of perception of the hazard when almost-flat sites are developed [60] compared with riparian settlements, where the flood threat is visible [61,62]. In a fast-growing population context, such as in rural Niger, another possible cause is the false sense of security that new inhabitants may have if they had not previously experienced a severe flood [57,63]. Finally, access to safe sites may be restricted owing to the lack of affordable lots. For policy implications, this study suggests increasing awareness of dangerous sites using hazard maps (Figs. 5 and 6) and flood sign warnings. In addition, we recommend identifying areas of town expansion where land pooling can be practised. This technique consists of temporarily pooling the land holdings in the expansion zone in public hands to plan the land subdivision, marking the lots corners, keeping part of the land for affordable lots, and selling another part of the lots on the market. The proceeds fund the construction of the stormwater drains. Lots provided with the utilities are returned to landowners in proportion to the land area with which they haved contributed to land pooling [64]. Without land pooling, future housing remains undrained and prone to flooding.

5.2. Risk-reduction measures

Generally, house retrofitting and flood-prone asset awareness are not recommended in the literature on sub-Saharan Africa (Table A2) because FRAs using low-resolution digital terrain models do not identify the assets in the flood zone [16]. This study explains the possible reasons of this problem. First, there is a widespread lack of knowledge among practising scholars regarding the standardised definition of FRA, which includes analysis and evaluation [20]. The risk evaluation phase is based on risk-reduction measures and their potential impact, and is finalised for decision-making in accepting or treating risk. Consequently, these measures remain generic or unspecified. Second, in sub-Saharan Africa, FRA is rarely required in local planning processes. Regarding policy implications, it is crucial to integrate residual risk analysis into local development plans.

5.3. Risk-reduction efficiency

Catchment treatment (trapezoidal bunds, half-moons, stone lines, and gabions), house retrofitting (metal roof and door flood barrier), raised latrines and barns, and hazard mapping can reduce the flood-prone zone by 10–24% and 21–48% on rainy days for RP3 and RP20, respectively. Therefore, treatment can reduce risk levels by 18–71% (RP3) and 23–59% (RP20). These values confirm the positive effect of soil and water conservation measures on agro-pastoral activities [65] and downstream settlements.

A benefit/cost analysis [19] indicated that efficiency is related to the size of the catchments to which the towns belong. When the catchment was small (Guecheme, Gagila, and Sabon Birni), the area to be treated was smaller; therefore, the cost component was lower, and the efficiency was higher. Risk reduction is less efficient for large catchments (Tessa). Thus, flood risk reduction is related to the size of their catchments but not to the size of the towns [21–23]. This implies that the catchment area in the Dosso region must be known and be part of the criteria for prioritising treatment with trapezoidal bunds, half-moons, stone lines, and gabions.

5.4. Public participation

Public participation provides information on the critical rain threshold trends over time, triggers of material and immaterial flood damage, and vulnerability and replacement value of assets. In addition, public participation contributes to the criteria for choosing measures, and recall the benefits of pluvial floods in semi-arid sites (Fig. 4). Thus, its contribution extends beyond providing local observers to monitor water bodies [66], identifying the exposed assets [67], in-place coping strategies [52], and causes of disasters and hazards [68], and implementing new coping strategies [24,69]. Therefore, this study provides an example of local and scientific knowledge integration in an under-investigated field [26]. For policy implications, public participation at all stages of an FRA should be encouraged, and the process should be legally defined.

5.5. Limitations

This study has several limitations. First, the accuracy of the flood-prone zones was limited by the cell size (10 m) of the digital terrain model. A significant improvement could be achieved with a more detailed morphology using an unmanned aerial vehicle (UAV cell size 0.1–1 m), as reported for the settlements along the Sirba River [62] where poor vegetation coverage makes this photogrammetry technique feasible. A more accurate perimeter of flood-prone areas is essential for determining sites for settlement development. This further study is only justified in settlements with the highest benefit/cost ratio and which are undergoing the most rapid physical expansion.

Second, SWAT modelling was performed over ungauged catchments; therefore, a regionalisation approach was implemented. As previously assessed [44], this solution is commonly accepted and implemented today; it has enabled researchers to exploit the potentials of hydrologic models in data scarce catchments. However, it must be considered that the procedure is exposed to higher uncertainty since the calibration and validation processes are conducted outside the target catchment.

Third, the identification of assets was limited because they were partly ascertained (homes, warehouses, and schools) and partly estimated (latrines, barns, and wells). In this case as well, images from a UAV would provide a more precise inventory of assets.

Fourth, indirect damages, such as road temporary road inaccessibility, closure of markets, and an increase in water-borne diseases from pluvial flooding were not considered.

Despite these limitations, the findings confirmed the hypothesis that participation and local knowledge integration, within the FRA standardised by ISO 31010 provide a valuable decision-making tool in situations characterised by scarce information availability and limited resources.

Suggestions for future research may include (i) using UAVs to increase digital terrain model accuracy and to accelerate asset identification, (ii) stage placement and registration of water depth during critical rainfall, and (iii) estimating the monetary cost of immaterial damages.

6. Conclusion

This study proposes a novel approach to overcome the limited design, accuracy, and completeness of current FRAs by accurately identifying assets, risk treatment, public participation, and local knowledge integration in all FRA steps. Through this approach we discovered that Guecheme, Tessa, Sabon Birni, and Gagila contained 21% and 32% of the built-up areas in the flood-prone zones with RP3 and RP20, respectively. Additionally, the built-up areas in flood-prone zones with RP3 and RP20 contained 54% and 79% of the housing stock exposed to floods, respectively. The deviation between the flood-prone zones and housing stock is large enough to question the significance of FRAs that consider only the flood-prone area to estimate risk.

The study proposed 10 measures. When implemented at catchment and building scales, these measures can reduce the pluvial flood risk following frequent and less frequent rainfalls by 18–71% and 23–59%, respectively. These measures had a higher benefit/cost ratio (2.2–7.3) for frequent floods for small catchments and a lower benefit/cost ratio (0.6) for infrequent floods for large catchments. Moreover, mapping the flood-prone zone is essential for the safer expansion of the built-up area.

FRAs may appear unsuitable for towns such as those considered in this study. However, if these towns grow at the rate observed in the last decade, they will be significantly larger and more populous in ten-years. These towns could extend into flood prone areas without knowledge of flood zones. This justifies the strengthening of local governance and modernisation of decision-making tools. Immediate action is important because training local officers and operationalising a geodatabase to reduce flood risk will take a considerable time.

To contribute to implementing the Sendai framework for disaster risk reduction, in sub-Saharan Africa FRAs at the local scale must be far more detailed than they currently are. Therefore, merely identifying flood-prone areas is insufficient. The catchment surface, exposed assets, and numerous measures must be identified within a framework built on public participation. Only then will public participation be significant on deciding whether to treat or accept risk.

Author credit

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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 are available at the 5 tables included in the text and in the 6 tables at Appendix A of the manuscript.

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Appendix A

Table A1
Nineteen flood assessments in Africa 2009–2022.

Settlement, Country ISO	Hazard	Flood prone area %	Receptors	Public participation	Validation	Reference
Abidjian, CDI	Pluvial	34	No	No	No	[57]
Ambo, ETH	Pluvial		No	No	No	[70]
Asanta, GHA	Fluvial		No	Yes	No	[71]
Beira, MOZ	Pluvial, storm		No	Yes	Yes	[72]
Cairo, EGY	Pluvial		Building	No	No	[73]
Dire Dawa, ETH	Fluvial		Building	No	Yes	[46]
Douala, CAM	Pluvial	55	No	No	No	[74]
Ifo, NIG	Pluvial	32	Building	No	No	[75]
Kigali, RWA	Fluvial		Building			[76]
Lagos, NIG	Pluvial	30	No	No	No	[59]
Matola, MOZ	Pluvial		No	No	No	[77]
Mono, TOG	Fluvial		No	Yes	No	[78]
Oti, TOG	Fluvial	-	No	No	Yes	[79]
Ouagadougou, BFA	Pluvial		No	No		[58]
Pantedo, STP	Storm surge		No	No	No	[80]
Port Louis, MUS	Pluvial		No	No	No	[81]
Sheeva Robit, ETH	Pluvial	18	No	No	Yes	[45]
Sirba, NER	Fluvial, pluvial		House	Yes	Yes	[61]
Tarkwa, GHA	Fluvial	42	No	No	No	[83]

Table A2

Measures recommended by thirteen pluvial flood risk assessments in sub-Saharan Africa.

Frequency	Recommendations		
	Measures	Settlements	Reference
8	Storm water drainage	Beira, Dar es Salaam, Douala, Garbey Kourou, Larba Birno, Talle, Tarkwa, Toure	[62,70,72,74,83,85]
6	Early warning system	Ambo, Garbey Kourou, Ifo, Larba Birno, Talle, Toure	[62,70,75]
5	Access to weather forecasts	Chikafa, Chitsungo, Kanongo, Monozi, Mushumbi	[84]
5	Poverty reduction	Chikafa, Chitsungo, Kanongo, Monozi, Mushumbi	[84]
5	Non structural	Chikafa, Chitsungo, Kanongo, Monozi, Mushumbi	[84]
4	Storm water storage	Ambo, Cairo, Port Louis, Tarkwa	[70,71,82,83]
4	Contingency plan	Garbey Kourou, Larba Birno, Talle, Toure	[62]
4	Drills	Garbey Kourou, Larba Birno, Talle, Toure	[62]
4	Rural radio	Garbey Kourou, Larba Birno, Talle, Toure	[62]
4	Raised wells, latrines	Garbey Kourou, Larba Birno, Talle, Toure	[62]
3	Discourage lowlands development	Ga-Kgapane, Lenyenye, Nkowankowa	[86]
3	Building code enforcement	Ambo, Port Louis, Tarkwa	[70,82,83]
3	Evacuation routes	Ambo, Beira, Ifo	[70,72,75]
2	Flood hazard/risk maps	Ambo, Sheva Robit	[45,58]
2	Shelters	Ambo, Ifo	[70,75]
2	Green infrastructure	Port Louis, Shewa Robit	[45,82]
1	None	Ouagadougou	[58]
1	Participatory planning	Ambo	[70]
1	Relocation	Dar es Salaam	[85]
1	Two floor buildings	Ambo	[70]
1	Afforestation	Ambo	[70]
1	Rainwater infiltration	Port Louis	[82]
1	River renaturation	Port Louis	[82]
1	Catchment treatment	Ambo	[70]

Table A3

Damage in the four towns 1998–2019 according to the open access database on floods in Niger (BDINA).

Damage	Gagila	Guecheme			Sabon Birni	Tessa	
	2015	2014	2015	2016	2019	2010	2016
mm		67					90
People	183	1275	129	140	151	650	375
Houses	40		37	15		117	22
Fields		1.5			6	8	

People: the number of affected persons; Fields: the number of flooded fields when the yield is lost.

Table A4

Average replacement value of frequently flooded assets.

Asset	Quantity	Euros
House	30 m^2 unit	750
Latrine	1	225
Barn	1	76
Class	1	8140

Table A5

Average costs of selected measures for pluvial flood risk treatment.

Measures for risk treatment	Quantity	Euros
Well disinfection	1	60
Stone lines	0.01 km^2	114
Half-moons	0.01 km^2	451
Corrugated iron roof	30 m^2	168
Raised latrines	1	229

Table A6
Average (Avg) and maximum (Max) hydraulic depth in the built-up area according to RP3 and RP20 in the four towns.

Return period years	Gagila		Guecheme		Sabon Birni		Tessa	
	Avg m	Max m	Avg m	Max m	Avg m	Max m	Avg m	Max m
3	0.14	1.63	0.24	2.59	0.34	3.17	0.51	2.91
20	0.20	2.07	0.42	2.82	0.39	3.29	0.61	3.33

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