Method for pluvial flood risk assessment in rural settlements characterised by scant information availability

MethodsX 8 (2021) 101532

Contents lists available at ScienceDirect

MethodsX

journal homepage: www.elsevier.com/locate/mex

Method Article

Method for pluvial flood risk assessment in rural settlements characterised by scant information availability

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A B S T R A C T

In tropical regions, heavy precipitations may lead to catastrophic flooding due to the degradation of catchments and the expansion of settlements in flood prone zones. In the current situation, where information on rainfall and exposed assets is either scant, or requires significant time to be collected, pluvial flood risk assessments are conducted using participatory tools, without any scientific support. Another option is to use satellite precipitation products, digital terrain models and satellite images at high to moderate-resolution. However, these datasets do not reach the required accuracy at the local scale. Consequently, the potential damages and the evaluation component of risk assessment are often missing. Risk evaluation is pivotal for informed decision-making, with regards to the choice of treating or accepting the risk, implementing more effective measures, and for determining the safest areas for development. We proposed an improved method for assessing the risk of pluvial floods, which merges local and scientific knowledge and is consistent with the ISO 31010 standard. The method was successfully applied in five rural settlements in Niger and can be replicated in areas where information is scarce.

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https://doi.org/10.1016/j.mex.2021.101532

A R T I C L E I N F O
Method name: ISO 31010 Risk management-Risk assessment techniques
Keywords: Africa, Built-up expansion, Disaster risk reduction, Runoff, Dosso region, Local knowledge, Niger, Community participation, Participatory mapping, Residual risk, Risk evaluation, Risk reduction, Risk treatment, Traditional knowledge
Article history: Received 2 April 2021; Accepted 24 September 2021; Available online 25 September 2021

Specifications table

Subject Area	Engineering
More specific subject area	Pluvial flood risk assessment
Method name	Pluvial flood risk assessment in rural settlements characterised by scant information availability
Name and reference of original method	ISO 31010 Risk management-Risk assessment techniques
Resource availability	Mendeley repository: doi: 10.17632/x479jhbsjh.1 Daily precipitations: Direction de la Météorologie Nationale, Niamey, Niger Digital terrain model: Intermap Technologies Inc. Runoff coefficient: Soil and Water Assessment Tool (SWAT) software Hydraulic analysis: Hydrologic Engineering Center-River Analysis System (HEC-RAS) - 5.0.7 Potential damages: Very high-resolution satellite images (World View 2 and Google Earth Pro) Historical damages: ANADIA Niger Floods Database (https://www.inondations-niger.org/) Replacement cost of damaged assets: Zaneidou (2015) and local knowledge Cost of risk reduction measures: Zaneidou (2015) and local knowledge

Method description

Introduction

In tropical regions, rapid population growth has led to the expansion of human settlements in flood prone zones; this phenomenon was primarily observed in urban areas. However, in rural areas, heavy rainfalls quickly escalate into disasters due to a higher rate of non-durable houses and the lack of storm water drainage. The United Nations Sendai Framework for Disaster Risk Reduction (2015) encourage member countries to expand risk knowledge at a local scale [1]. Despite that, pluvial flood risk assessments (FRA) at a local scale are still infrequent. FRAs are usually based on local knowledge, or only on scientific-technical knowledge. Global precipitation datasets, digital elevation models, moderate to high resolution satellite imagery, are the most commonly sources of information. However, the performance of satellite precipitation products for hydraulic modelling is still inadequate for operational purposes [2]. Remote sensing to observe flooded areas is inaccurate [3] and the use of hydraulic modelling remains occasional in many countries [4]. Little attention is paid to exposure and vulnerability [5], although recent global research has established that catchment discharge is driven more by settlement expansion and other human interventions than by climate change [6–7]. As a result, understanding of damage determinants remains incomplete and usually limited to direct damage [8]. Hence, pluvial FRA is mostly analysis, and lacks the evaluation component that the ISO 31010 standard requires [9]. As a result, FRA is inadequate for use in decision-making for policies regarding the development required to manage pluvial floods.

Recent literature reviews recommend four main improvements of FRAs at the local scale. First, integrating local and scientific - technical knowledge [10]. So far, FRAs engage local knowledge mainly to identify risk reduction measures [11] and to understand how a community mobilises during disaster recovery [12]. Sporadically, FRAs engage local knowledge to characterise threats, and to understand their dynamics and impact over time [13]. The second required improvement involves transitioning from a static approach of conventional probabilistic likelihoods that consider catchments as unchanging in time and space, to a scenario-based approach [14]. The third improvement involves

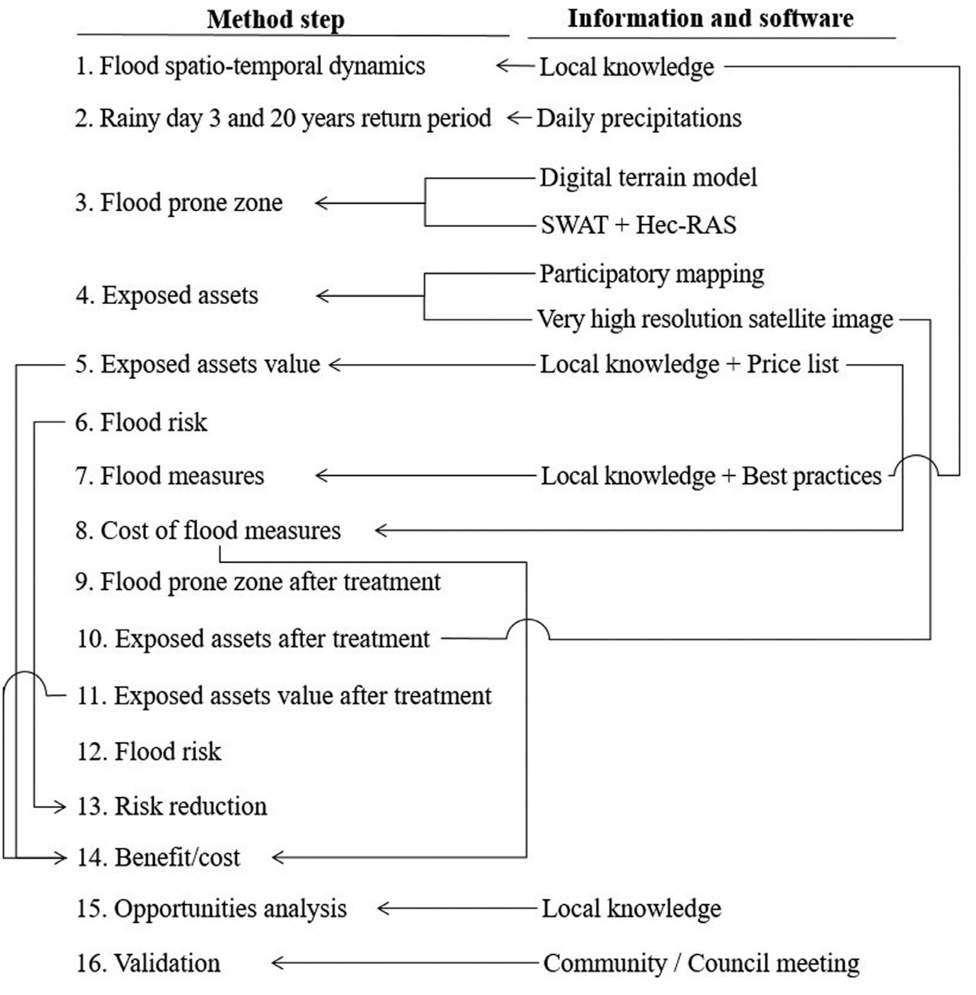

Fig. 1. Flowchart of the pluvial FRA.

the use of open access data, more accurate than the ones in wide use [15]. The fourth improvement requires broadening the spectrum of risk treatment benefits to include intangibles and opportunities. The primary concern among these is the post disaster build back better [16,17].

This improved method for pluvial FRA demonstrates how to involve local knowledge at all phases of risk assessment. It also presents how to employ various scenarios in risk assessment. Finally, the integration of local open access dataset on flood damage, open access very high resolution satellite images, and low-cost digital elevation models in hydraulic modelling have been illustrated. This method establishes the context, characterize hazards, establishes the accuracy of hazard mapping, and based on scenarios, evaluates the risk. Finally, the suitability of the risk treatment measures is discussed with the local communities (Fig. 1).

Context and hazard identification

The pluvial FRA was conducted in two rural towns (Guecheme and Tessa, with populations of 8500 and 5000 in 2012, respectively) and three minor settlements (Gagila, Sabon Birni, and Takouidawa,

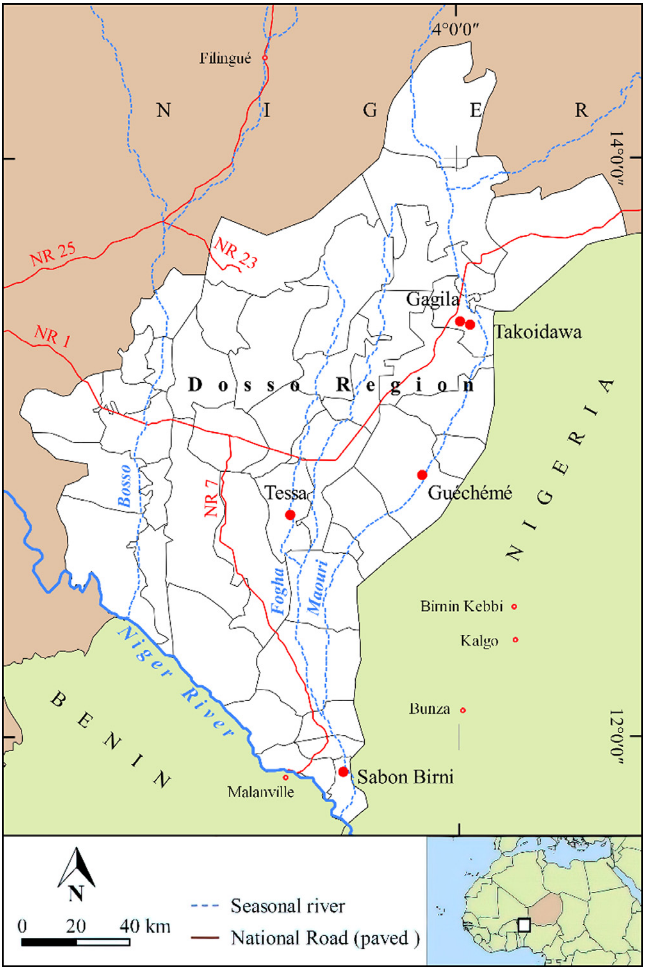

Fig. 2. Five rural settlements where the assessment was conducted.

with populations of 1700, 6000, and 808 respectively) in Niger. These human settlements have experienced repeated damage due to pluvial floods over the last ten years and are expanding faster than cities [18] (Fig. 2).

Three meetings with technicians, local administrators, and the communities provided an insight that purely probabilistic methods could not have been derived from global or national datasets. For example, the hazards each community was exposed to, the duration of heavy precipitations, their impact on the exposed assets, the causes of flood damage, and the dynamics of assets over time are typical local knowledge (Table 1).

The date and subject of the meetings were announced in advance to each community and all the members were invited to attend. Meetings were accompanied by participatory mapping and on-site inspection in areas where major flood damage had occurred (Fig. 3).

The 99th centile daily rainfall recorded over the last thirty years in the municipal capital town enabled the identification of the temporal dynamics of extreme rainfall (Fig. 4).

The extent of damage as registered by the ANADIA Niger Floods Database in each flooded human settlement during the last 20 years [19], cross-referenced with daily rainfall records obtained from

Table 1
Causes of flood damage in the five rural settlements.

Causes of flood damage	Gagila Takouidawa	Guecheme	Sabon Birni	Tessa
Heavy rains	•	•	•	
Runoff	•	•	•	
Lack of drainage		•		
Rainwater stagnation				•
Road network orientation				•
Settlement expansion	•	•	•	
Housing physical vulnerability		•	•	•
Low well curb stone				•
Soil degradation (leaching) following cultivation	•			
Reduction of catchment vegetation	•	•	•	
Water and soil conservation works in the catchment		•	•	•
Inadequate protection of creek banks	•	•	•	•

Table 2
Daily rainfall (mm) for related return periods in the five human settlements.

Return period (years)	Gagila Takouidawa (mm)	Guecheme (mm)	Sabon Birni (mm)	Tessa (mm)
3	76	68	86	80
20	118	120	131	113
50	137	147	151	127
100	151	170	166	138

Fig. 3. Participated flooded areas mapping in Takouidawa, May 2020.

the Directorate national for meteorology, allowed the identification of the minimum rainfall threshold beyond which damage occurs (critical rainfall) (Table 2).

Subsequently, damage is caused by altered catchment surface, asset exposure, and physical vulnerability when the minimum rainfall threshold is lowered over time, without an increase in the intensity or frequency of rainfall.

The integration of local and scientific knowledge takes place during all phases of the FRA (Table 3).

Risk analysis

The pluvial flood risk (PR) is the product of hazard (H) and potential damage (PD): PR = H × PD [20]. The hazard is the probability of a rainy day with return periods of 3 (RP3) and 20 (RP20) years, which highlight highly probable events and less probable but more intense events, corresponding to

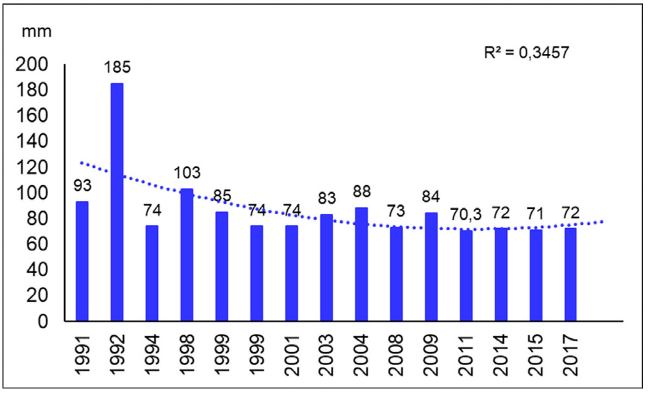

Fig. 4. 99th centile rainfall at Guecheme 1990-2018.

Table 3
Integration of local and scientific knowledge into risk assessment.

Risk assessment element	Knowledge	
	Local	Technical
Hazard	Critical rain duration Pluvial flood dynamics Flooded zones map	Daily precipitations Hazard map
Damage	Driver Critical precipitation causing damage Assets vulnerability Replacement value	Return period of critical precipitation Assets location
Criteria for selecting risk reduction measures	Known by the community Best practice Community willingness to implement measures Use of local skills Environmental impact	Effectiveness in risk reduction Maintenance requirements Win-win measures
Risk evaluation	Immaterial damage Non-economic benefits from risk treatment	Potential damages Potential impact of measures Benefit/cost analysis

the thresholds at which the damage initiated. Meetings with communities highlighted that runoff impacts latrines, wells, and sometimes houses. Heavy rainfall impacts on the roof of houses, barns, schools and can lead to a collapse.

The return periods were analysed by applying the extreme value theory to the maximal daily rainfall for each year. Four probability distribution functions were tested: generalised extreme values (GEVs), Gumbel, exponential, and log-normal. Fitting tests (Pearson and Anderson-Darling) were employed to select the best distribution [21]. The longest rainfall time series (Guecheme and Sabon Birni) had the best performance with the GEV probability distribution, whereas the shorter rainfall time series (Tessa and Gagila) best reflected the Gumbel distribution [22] (Table 4).

The estimation of flood-prone zones involved hydrological analysis and hydraulic modelling. The calculation of the adimensional runoff coefficient (C), which is defined as the ratio of the runoff (R) to the precipitations (P) expressed in millimetres ($C = R/P$) was performed using the soil and water assessment tool (SWAT) software [23–24] in the current conditions (B) and following risk treatment (T). SWAT is a continuous and deterministic hydrological model at a catchment scale, developed by the Agricultural Research Service of the United States Department of Agriculture. The hydrological model simulated seepage and overland flow for the entire duration of the rainfall time series and

Table 4
Characteristics of the daily rainfall time series used.

Characteristics	Gagila Takouidawa	Guecheme	Sabon Birni	Tessa
Rain gauge location	Kieche	Guecheme	Tounouga	Tessa
Time series	1999-2018	1981-2018	1981-2018	1999-2018
Total years	20	38	38	20
Complete years	17	38	30	18
Probability distribution	Gumbel	GEV	GEV	Gumbel

Table 5
Runoff coefficient averages for current conditions (B) and after treatment (T), RP3, and RP20.

Return period (years)	Gagila Takouidawa		Guecheme		Sabon Birni		Tessa	
	B	T	B	T	B	T	B	T
3	0.47	0.34	0.41	0.30	0.34	0.26	0.37	0.31
20	0.59	0.47	0.53	0.43	0.54	0.47	0.45	0.41

Table 6
Soil roughness according to land cover as defined by Manning coefficient n ($s/m^{1/3}$).

Land cover	Soil roughness n ($s/m^{1/3}$)
Tiger bush degraded - managed	0.035–0.04
Terraced crop fields	0.04–0.05
Gardens	0.10
Ponds	0.04
Pasture well - badly managed	0.025–0.03
Unpaved road	0.02
Bare soil–Bare soil provided with SWC*	0.025–0.03
Dense vegetation	0.10
Orchard	0.06
Human settlements	0.07

* SWC-Soil and Water Conservation.

allowed the runoff coefficients to be determined under conditions B and T for RP3 and RP20 in the five settlements.

The concentration time (C_T), calculated with the Ventura formula with the area (a) expressed in kilometres and the adimensional slope of the riverbed (S) ($C_T = 0.127 \ x \ a^{0.5} \ x \ S^{-0.5}$); the calculated values were 3.2 h (Sabon Birni), 3.7 h (Guecheme), 4.1 h (Tessa), and 7 h (Gagila-Takouidawa). The runoff coefficients in the B state varied from 0.34 to 0.59 as the return period increased (Table 5).

The hydraulic analysis of the settlements was conducted through two-dimensional hydraulic models created using the hydrologic engineering centre-river analysis system (HEC-RAS) software, version 5.0.7 [25]. The model geometry was determined using a digital terrain model with a cell size of 10 m by Intermap Technologies Inc. The soil roughness was defined according to the land cover conditions and varied between 0.025 $s/m^{1/3}$ (for bare soil) and 0.1 $s/m^{1/3}$ (for gardens and dense vegetation) (Table 6).

The flow conditions of the models were simulated by rainfall and hydrographs distributed along the main hydrography. The hyetographs reflected the typical form of Sahelian storms parameterised by Balme [26], wherein the duration of the convective system (D_C) amounts to approximately 1 h with a symmetrical form; the maximum intensity was based upon the total rainfall recorded at the rain gauge while the storm lasted a few hours with constant low-intensity rainfall tail (I_S) of 1.5 mm/h. (Fig. 5).

The hyetographs depict the net rainfall intensity (I_N) which represents the rainfall intensity (I) reduced by the runoff coefficient (C) calculated through hydraulic modelling ($I_N = I \times C$). The hydrographs were constructed in a triangular shape in which the climb was equal to the concentration

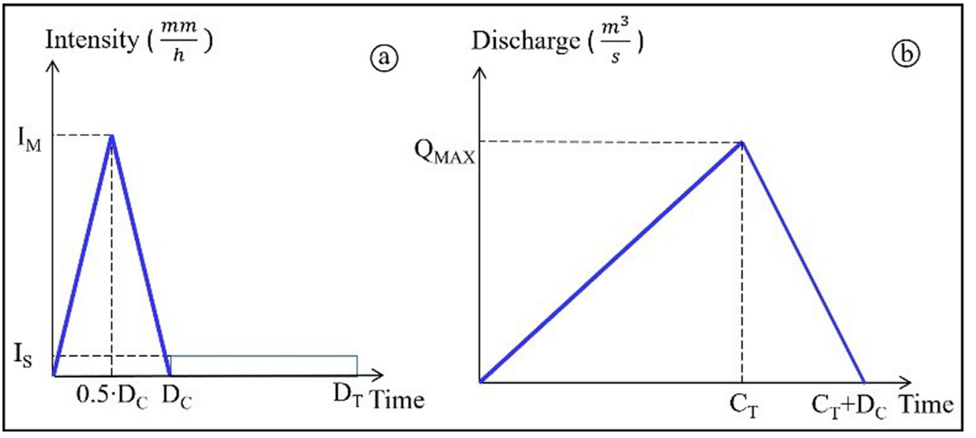

Fig. 5. Forms and parameters of the hyetographs (left) and hydrographs (right) used in the hydraulic model.

Table 7
Comparison between local perception and hydraulic modelling of flood zones.

Flood prone zone	Local perception	Hydraulic model
RP3 (very probable)	Broad coincidence	
RP20 (probable)	None	Yes

time (C_T) of the catchment and the descent was equal to the duration of the convective rainfall. Given the intermittent nature of the local hydrography, the minimum discharge amounted to zero and the maximum discharge was calculated using the rational method. In the said method the discharge (Q m^3/s) was calculated as the product of the runoff coefficient (C), net rainfall average intensity during convective rainfall (I_N mm/h) and area of the catchment (a km^2): $Q_{max} = (C * I_N * a)/3.6$ [27].

Four simulations were conducted for each settlement, in accordance with the two return periods and conditions B and T of the catchments. The flood-prone zones for each scenario were defined as the area in which the hydraulic depth exceeds 10 cm, which is a value that surpassed the entrance threshold of the homes (Fig. 6).

The flood zone identified by participatory mapping was compared with the flood zone identified using hydraulic modelling. This depicted the degree of coincidence between local observation and the model's dependence on the probability of the flood occurring (Table 7).

When the flood zone based on local knowledge did not coincide with the one computed through hydraulic modelling, a restitution session with the community was organised.

The assets exposed in the flood-prone zones with RP3 and RP20 years were identified through visual photo-interpretation of World View-2 very-high-resolution satellite images captured in September 2019. Each exposed asset was then visited by a local team to ascertain its use (dwelling, storage, granary, latrine, school, well) and its physical vulnerability to flooding (type of roof, masonry, presence of threshold at entrance, elevation above ground) (Table 8).

Each type of asset was assigned a replacement value determined through discussion with local communities (Table 9). However, it was not necessary to use the stage-damage curve in the settlements: the homes were typically built from non-durable or semi-durable materials. When water entered the homes due to missing or low thresholds, or due to an earthen roof, they collapsed shortly after.

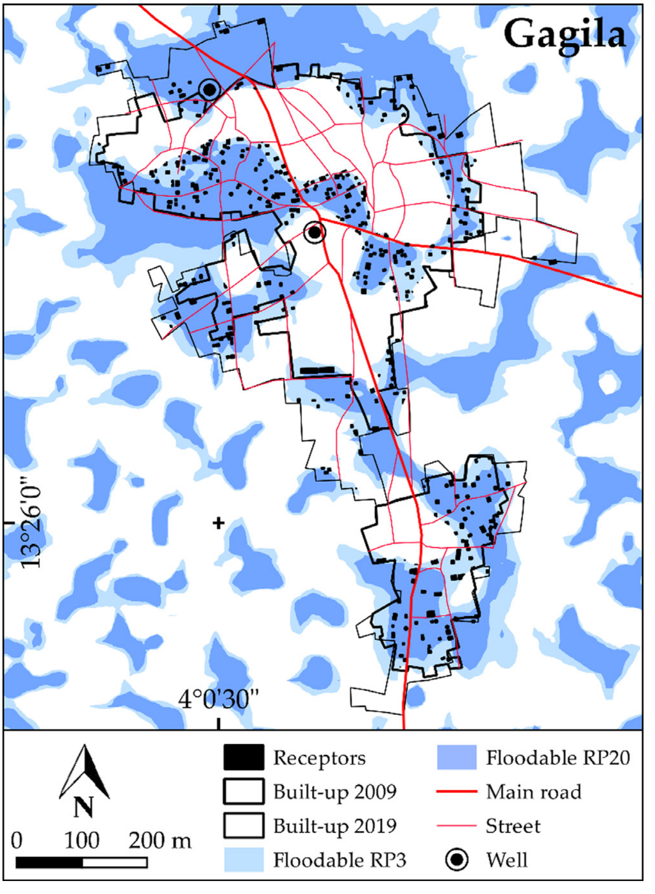

Fig. 6. Assets in flood prone zones in the rural settlement of Gagila.

Table 8
Number of assets in very probable (RP3), probable (RP20), and improbable flood zone and built-up expansion 2020-2029.

Flood zone	Asset	Gagila	Takouidawa	Guecheme	Sabon Birni	Tessa
Very probable	House	239	103	1070	1165	168
	Latrine	184	184	357	388	40
	Barn	27	5	45	205	62
	Class*	0		4	0	0
	Well	0			0	0
Probable	House	378	163	1624	1569	260
	Latrine	243	243	541	523	40
	Class*	3		9		0
	Barn	32	6	4	287	96
	Well	2	2	1	0	1
Improbable	House*	306	229	204	326	196
Expansion 2020-29	House	283	192	324	282	52

* Earthen roof only

Table 9
Substitution value of assets and risk reduction costs used for evaluating the risk.

Item category	Item	Gagila-Takouidawa (Euros)	Guecheme (Euros)	Sabon Birni (Euros)	Tessa (Euros)
Asset	House, 30 m^2	457	762	457	762
	Latrine	229	244	229	244
	Barn	107	305	76	114
	Class	5332	5332		
	Well disinfection	61	61		
Measure	Stone lines, 0.01 km^2	114	114	114	114
	Half-moons, 0.01 km^2	451	451	451	451
	Corrugated iron roof, 30 m^2	168	168	168	168
	Raised latrines	229	229	229	229

Table 10
Pluvial flood risk for RP3 and RP20 in current conditions (2019) expressed in euros.

Return period years	Determinant	Gagila	Takouidawa	Guecheme	Sabon Birni	Tessa
3	Hazard	0.33	0.33	0.33	0.33	0.33
	Damage	155,658	89,556	1,192,510	921,042	142,437
	Risk	51,367	27,263	357,692	472,793	43,417
20	Hazard	0.05	0.05	0.05	0.05	0.05
	Damage	503,375	324,718	2,181,647	1,701,779	407,964
	Risk	25,169	16,145	109,075	85,089	20,413

Pluvial flood risk

The value of the exposed assets expressed in euros was multiplied by the probability of precipitation with RP3 and RP20 to determine the risk in current conditions (Table 10).

Risk evaluation

In each settlement, a meeting with the mayor and municipal technicians (6–7 December 2018), one with the community of women, and another with the community of men (15–22 May 2019) identified ten measures to reduce the risk.

Local knowledge enabled us to understand that rain-flood damage was not a result of climate change and its impact on the frequency and extent of extreme rainfall, but to the degradation of the catchments to which human settlements belong, the exposure, and physical vulnerability of assets.

Consequently, the risk assessment employed four scenarios. The first two scenarios considered frequent flooding (RP3) and less frequent flooding (RP20) respectively. In both the cases the risk was not treated. The settlement continued to expand without the awareness of the flood zones. The third and fourth scenarios consider frequent (RP3) and less frequent (RP20) flooding respectively. In this case, however, the runoff was reduced with trapezoidal bunds, stone lines, and half-moons within the catchments (Fig. 7). Corrugated iron sheet roof for adobe houses was generalised. The expansion of the built-up area only occurred in areas with a low probability of flooding.

The cost of risk treatment was estimated using local prices and was compared to the price list prepared by Zaneidou [28]. The treatment of the catchments (condition T) created a smaller flooding perimeter, as calculated using the hydraulic model. In addition, the adoption of corrugated iron sheet roofs in zones with a low probability of pluvial flooding eliminated the risk of collapse of houses with earthen roofs.

The risk of flooding in the T condition was determined by multiplying the replacement value of the assets within the flood perimeter after the catchment treatment by the probability of precipitation with RP 3 and RP20. The level of risk in the T condition represented the residual risk (Table 11).

The amount of land needed for the development of the settlements in the next decade was estimated assuming a rate of expansion equal to the one observed between 2009 and 2019. The

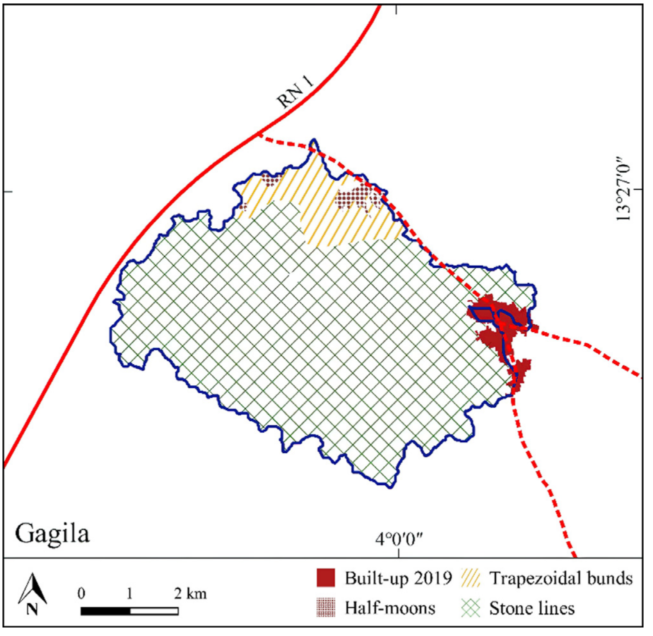

Fig. 7. Localisation of the risk reduction measures in the catchments of Gagila.

Table 11
Risk and residual risk for daily rainfall with RP3 and RP20.

Risk	Gagila		Takouidawa		Guecheme		Sabon Birni		Tessa	
	€	%	€	%	€	%	€	%	€	%
RP3 risk B	51,367	100	27,263	100	357,692	100	472,793	100	43,417	100
RP3 risk T (residual)	35,283	69	20,566	75	103,818	29	265,832	56	35,800	82
RP20 risk B	25,169	100	16,145	100	109,075	100	85,089	100	20,413	100
RP20 risk T (residual)	10,562	42	11,578	72	44,445	41	65,353	77	9,293	46

Table 12
Damage reduction benefits (B)/ risk treatment costs (C) ratio in the five rural settlements.

Return period (years)	Gagila B/C	Takouidawa B/C	Guecheme B/C	Sabon Birni B/C	Tessa B/C
3	0.2	0.2	5.7	0.2	0.09
20	1.4	1.6	3.3	1.6	0.8

existence of non-flood-prone areas contiguous to the existing built-up area, which was a requirement to satisfy the estimated demand for land development by 2029 was verified.

Finally, the benefit/cost ratio for the reduction of the pluvial flood risk was calculated. Benefit is defined as the difference between the potential damage in condition B and condition T. The potential damage in condition B also included damage to the buildings which were expected to be constructed between 2020–2029. This was obtained by applying the construction rate of buildings between 2009–2019, on the assumption that the construction takes place without considering the flood-prone zones. In condition T, we assumed that the flood-prone zones were known and that the expansion in 2020–2029 would occur in non-flood-prone zones. The cost was considered to be the risk treatment cost (Table 12). The greater the value of the benefit/cost ratio above 1, the more efficient the treatment was considered [29] (Fig. 8).

Table 13
Other benefits and opportunities analysis from pluvial flood treatment in the five rural settlements.

Other benefits and opportunities	Gagila	Takouidawa	Guecheme	Sabon Birni	Tessa
Risk awareness	•	•	•	•	•
Flood monitoring	•	•	•	•	•
Avoid road interruptions					•
Growing rice instead of millet	•				
Recession farming	•			•	•
Commercial gardening				•	•
Fish-farming					•

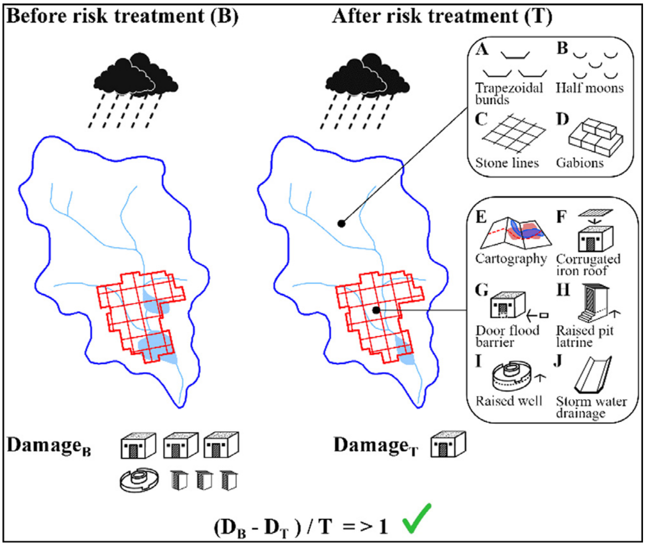

Fig. 8. The pluvial flood risk evaluation using benefit/cost analysis.

The benefit/cost assessment only consider the benefit of damage reduction. Local knowledge helps to identify the other benefits, which are usually not quantifiable in monetary terms. Risk assessment can highlight these benefits and bring them to the attention of decision-makers. These benefits may include increased community awareness of risk, increased mobilisation in monitoring hydro-climatic threats, and highlighting opportunities that more water can offer in a semi-arid context for agro-pastoral development with the introduction of new crops (Table 13).

Validation

The flood-prone zones were validated based on the assets struck during recent floods, whose position was detected by GPS in December 2018 and May 2019. The relevance of the measures was reconsidered during a final meeting with each local community held between 22nd and 25th March 2021.

Conclusion

This method for improved pluvial FRA introduces four novelties: first, systematic engagement of local knowledge in all steps of FRA, and the integration of local and scientific-technical knowledge for analysing and assessing risk.

Second, the use of four risk scenarios based on local knowledge. First and second scenarios involved continuing as usual in case of frequent and less frequent pluvial flood. However, third and fourth scenarios involved treating the catchments, reducing the exposure of existing and future assets in case of frequent and less frequent flood.

Third, the use of open access very high-resolution satellite images for land cover analysis and assets identification and local open access datasets on flood damage.

Fourth, considering the opportunities presented by pluvial floods to increase the agro-pastoral development other than build back better. The method was applied to five rural settlements in Niger. The identification of risk reduction measures, simulation of their impact on the extent of the flood zone, and consequent reduction in the number of exposed assets enabled the estimation of the residual risk and the benefit/cost ratio. Immaterial benefits and opportunities from pluvial flood were also considered. These estimates facilitated informed decision-making regarding risk treatment or acceptance of risk. This method is replicable in rural locations where information is scarce. It provides a low-cost alternative to FRAs based on global datasets, more accurate results, and local community involvement.

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.

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