Assessment of Smallholder Farmers' Mitigation Strategies to Climatic Hazards in the Inland Valleys of Central Benin: The Case of Drought and Flood

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Abstract

Floods and droughts pose significant climatic threats to the stability of Benin's agro-economic systems, particularly affecting the livelihoods of smallholder farmers in inland valleys. In the Sudano-Guinean zone, where rainfed agriculture predominates, these regions are highly susceptible to climatic hazards such as drought and flooding. However, the dynamics, impacts, and mitigation measures associated with these hazards remain poorly understood.

This study investigated the frequency and duration of drought and flood events and the mitigation measures adopted by 208 smallholder farmers across 26 inland valleys in Savalou, a commune with substantial agricultural potential. A mixed-methods approach was used: climatic data (temperature and precipitation) from 1991 to 2021 were analyzed with the Standardized Precipitation-Evapotranspiration Index (SPEI) to assess drought and flood hazards, while socioeconomic data were collected through 52 focus group discussions and structured surveys involving the selected smallholder farmers. Statistical and clustering analyses were employed to identify trends, spatial distributions, and the factors influencing the adoption of mitigation measures.

The results revealed that the south-eastern part of Savalou was particularly prone to flooding, with events lasting up to 7 months and a frequency of 37%, while the northern and central parts were more vulnerable to droughts, which could last up to 10 months and had a frequency of 53%. Severe droughts, such as those of 2001, and episodes of extreme humidity in 1991 and 2019 have highlighted significant climatic variability, further exacerbating the vulnerability of local farmers. In response, smallholder farmers have implemented various mitigation strategies, including adaptive agricultural practices, ecological restoration efforts, and technological infrastructure improvements. Socioeconomic factors, such as proximity to markets, membership in agricultural organizations, and support from external institutions, influenced the adoption of these strategies.

Keywords

Climatic hazards · Agricultural lowlands · Smallholder farmers · Hazards mitigation · West Africa

Introduction

Flood and drought represent some of the most disruptive climate threats, with significant socioeconomic impacts on nearly one-third of the global population (Sarkar 2022). These events are climate-hydrological phenomena driven by precipitation variability, which exerts different spatial and temporal effects depending on the scale. Predictive modeling indicates that the frequency of these events will increase in numerous regions worldwide over the twenty-first century (Hirabayashi et al. 2008). Globally, climate-induced disasters affected over 3.5 billion people between 2000 and 2019, with floods alone accounting for 44% of these events and droughts responsible for 34% (UNDRR 2020). The effects of these climatic events have intensified in recent decades, severely impacting agricultural systems and threatening the livelihoods of large segments of the global population, particularly in developing countries (Pratiwi et al. 2020). Studies reveal that extreme climatic events, including droughts and floods, reduce global cereal production by 10% annually, with some regions experiencing losses as high as 30% in specific years (Birthal et al. 2021). Furthermore, droughts and floods are recognized as the most impactful climatic event regarding economic damage, with an estimated $48 billion in global agricultural losses from 2005 to 2015 in countries classified as Least Developed (LDCs) and lower-middle-income in Africa, Latin America and the Caribbean (LAC), and Asia and the Pacific (FAO 2021). Floods also contribute significantly to the disruption of global economies, costing over $70 billion annually in damages, according to the EM-DAT database (UNDRR 2020). The heightened recurrence of these events challenges farmers' mitigation capacities and exacerbates food inequalities, especially in areas heavily reliant on rain-fed agriculture.

The situation is especially alarming in Africa, as the continent is highly vulnerable to climate change due to its heavy dependence on rain-fed agricultural systems and limited hazard management capacities (Pratiwi et al. 2020). The World Bank estimates that by 2030, the compounded impacts of climate variability could push over 122 million people back into extreme poverty, primarily in Africa and South Asia. In Sub-Saharan Africa, yield losses from extreme climatic events account for a substantial part of agricultural GDP, deepening farmers' economic precarity. Shiferaw et al. (2014) report that drought and flood alone account for approximately 80% of casualties and 70% of economic losses in this region. For instance, in the Sahel, successive droughts have reduced lowland agricultural yields by over 40%, affecting millions of people (Dossou-Yovo et al. 2019). These impacts are especially critical in regions like West Africa, where irregular rainfall and prolonged droughts threaten food supplies and exacerbate food insecurity (Ebi and Bowen 2016).

In Benin, the inland valleys serve as essential fallback agricultural areas in the face of climatic pressures, as most other agricultural spaces are urbanized or otherwise challenging to access. Although these valleys are widely recognized as potential wetland areas favorable for agriculture, especially rice cultivation, they are particularly vulnerable to droughts and floods, which disrupt agricultural cycles and compromise the livelihoods of smallholder farmers who rely on them. Bonou et al. (2018) highlight that these wetlands generate over 27% of Benin's agricultural income, and the loss of any portion due to flooding or drought would represent substantial economic losses. Consequently, Ekwezuo and Ezeh (2020) have noted that the frequent occurrence of these climatic hazards poses a major obstacle to economic development, given the impact on agricultural systems in developing countries. The World Bank suggests that, without developing useful intervention approaches, climate change could lead to increased agricultural prices and pose a risk to food security in less affluent areas, including Sub-Saharan Africa and South Asia.

Given these challenges, there is an urgent need to understand the distribution and frequency of these events in Benin's inland valleys and the existing approaches to mitigate these climate events. According to Ekwezuo and Ezeh (2020), such information is critical to enhancing our understanding of inland valley vulnerability to climatic hazards and strengthening existing resilience strategies. Kim et al. (2019) assign that assessing the occurrence of climatic hazards and existing mitigation measures forms a crucial bridge in developing practical solutions aligned with sustainable development goals (SDGs) related to poverty and hunger eradication and sustaining life on land, as drought and excessive moisture threaten these objectives.

This study assessed the occurrence and spatiotemporal distribution of droughts and floods, as well as the mitigation measures adopted in 26 geolocated inland valleys within the Savalou commune, a hotspot in the Sudano-Guinean zone of Benin, where inland valleys are extensively used for agricultural purposes. Specifically, the present study (i) evaluated the spatiotemporal occurrence of droughts and floods in the inland valleys of Savalou from 1991 to 2021 using the Standardized Precipitation-Evapotranspiration Index (SPEI), derived from daily precipitation and temperature data for each geolocated inland valley; (ii) explored and ranked the significance of various drought and flood mitigation measures adopted by smallholder farmers to face with these hazards; and (iii) assessed the socioeconomic factors driving the adoption of one or more mitigation measures in response to each of these hazards.

Methods

Study area

The study was conducted in 26 inland valleys within the commune of Savalou, located in the Collines department of Benin. Geographically, Savalou lies between 7°5′ to 7°77’ North latitude and 1°37′ to 2°33′ East longitude and is recognized as one of Benin's communes featuring extensive rain-fed inland valleys utilized primarily for rice cultivation. The commune experiences a Sudano-Guinean climate characterized by two distinct rainy seasons and an annual rainfall range of 1000 to 1200 mm (Lokonon 2017).

The region's soils are predominantly tropical ferruginous with a crystalline base, exhibiting highly variable properties supporting various agricultural activities, including cereals, root crops, legumes, and cotton (Djagba et al. 2019). The vegetation cover consists of gallery forests, saxicolous forests, and savanna mosaics, with landscapes transitioning from wooded to shrub savannas. Additionally, the area is marked by rich ethnic diversity, comprising groups such as the Adja, Dasha, Fon, Idatcha, Ifè, Lokpa, Mahi, and Nago (data from the field in 2022).

Sampling Process

In the municipality of Savalou, a grid was created using the QGIS mapping application to select inland valleys separated by a minimum distance of 5 km, ensuring that no single valley is counted multiple times. This preliminary mapping process yielded 49 initial points. Subsequently, an exploratory visit was conducted to assess these inland valleys' presence and agricultural viability. This visit identified 26 inland valleys deemed suitable for the current study.

Following this, two main categories of data were collected: climatic data and field survey data. The survey data collection was conducted at two levels: qualitative and quantitative. For the qualitative data, two focus group discussions (FGD) were held per inland valley, each involving 7 to 9 smallholder farmers—one FGD for women and one for men—resulting in 52 FGDs. In the quantitative phase, eight individuals from each inland valley, each with a minimum of 10 years of farming experience in these valleys, were randomly selected, yielding 208 smallholder farmers included in the quantitative analysis.

Data Collection

Two types of data were collected: climatic data and socioeconomic data.

Climatic Data

The climatic data consisted primarily of daily precipitation, minimum temperature, and maximum temperature records from 1991 to 2021 for each inland valley. These data were extracted from the WorldClim database, with a spatial resolution of 2.5 min, and were used to evaluate the occurrence and severity of drought and flood hazards in each inland valley. This assessment was based on event frequency and duration, using the Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010). According to Vicente-Serrano et al. (2010), the SPEI is used to classify dryness and wetness conditions based on specific thresholds. Values below -2 indicate extreme drought, while those ranging from -1.99 to -1.5 represent severe drought. Moderate drought corresponds to values between -1.49 and -1.0, whereas near-normal conditions fall from -0.99 to 0.99. Positive values denote wet conditions, with moderate wetness spanning from 1.0 to 1.49, severe wetness from 1.50 to 1.99, and extreme wetness characterized by values exceeding 2.

Socioeconomic Data

The collection of socioeconomic data started with an initial engagement phase involving local and traditional authorities in the identified inland valleys, ensuring permission to conduct research and facilitating the identification of key individuals who use, manage, and have firsthand experience with these areas' hazards. Guided by the support of these authorities, we organized focus group discussions (FGDs) separately for men and women, creating spaces where participants could openly share their experiences. These discussions explored various dimensions of their interactions with hazards, including how these events manifest, their frequency, the duration of floodwaters on their sites, and the mitigation strategies they either knew or actively employed. The insights gathered were instrumental in shaping a structured survey questionnaire. After being pre-tested with eight farmers to refine its clarity and relevance, the survey was administered to 208 smallholder farmers. It covered a broad range of topics, including demographic details (age, gender, ethnic group, education level, marital status), their experiences with climate hazards over the past decade (frequency of occurrences and their impacts on agriculture), mitigation measures adopted (such as specific farming practices, technological solutions, or land restoration efforts), and detailed socioeconomic characteristics (distance to roads and markets, quality of infrastructure, land ownership patterns, the origin of inland valley users, the proportion of women involved, farming systems, sources of inputs, institutional support, and affiliations with farmer organizations). The purpose of the survey was clearly explained to the participants, and their informed consent was obtained before each interview, which lasted between 40 and 70 min. Interviews were conducted during daylight hours, from 7:00 AM to 5:00 PM, to allow for direct observations of the inland valley sites and the participants' activities, ensuring a rich understanding of their challenges, strategies, and lived realities.

Data Analysis

Spatiotemporal Analysis of Drought and Flood Hazards

The Standardized Precipitation Evapotranspiration Index (SPEI) on a 12-month scale was used to assess the temporal occurrence of flood and drought hazards, while the SPEI on a 3-month scale was used to assess the spatial distribution of the hazards over the period from 1991 to 2021, following the classification by Vicente-Serrano et al. (2010).

The SPEI allows the evaluation of monthly differences between precipitation and potential evapotranspiration (PET) across timescales ranging from 1 week to 48 months. PET was estimated using the Thornthwaite equation, calculated from monthly precipitation (P) values and average monthly temperatures. The water balance (D) was then evaluated according to Eq. 1.

This approach provides a robust measure of climatic water deficits or surpluses, capturing both short-term and long-term climatic variability that affects water availability. Thus, it facilitates a comprehensive assessment of drought and flood severity.

$$D = P - PET \tag{1}$$

The SPEI value is then determined as a standardized value of the probability *P* derived from the distribution function *F(x)* of the water balance D obtained on a 12-month timescale (for temporal trend analysis) and a 3-month timescale (for spatial analysis), following the classic approach as outlined by Abramowitz and Stegun (1968):

$$\mathrm{SPEI} = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{2}$$

$$\text{With } W = \sqrt{-2\ln(P)} \text{ for } P \leq 0.5 \text{ and } W = \sqrt{-2\ln(1-P)} \text{ for } P > 0.5 \tag{3}$$

P is the probability of exceeding a given D value, defined as P = 1-F(x), and $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$.

Spatial Analysis Based on the 3-Month Scale SPEI Analysis

To assess the spatial distribution of flood and drought events, we employed the Runs Theory developed by Yevjevich (1967), which is widely used in flood and drought research (Achite et al. 2024). This theory considers events identical based on a predefined threshold, allowing for characterizing their onset, end, and frequency of occurrence. In our study, the threshold for drought periods was set as SPEI values below -1, and for humid periods (indicative of flood conditions), SPEI values were set at or above +1.

Using this threshold, we evaluated the duration and frequency of these hazards, which allowed us to assess both the extent (from beginning to end) and the trend of these occurrences. The duration of an event was defined as the longest consecutive period (in months) reaching the set threshold for each hazard type (≤ -1 for drought and ≥ 1 for flood). The hazard frequency (F_{iv}) was then calculated using the following formula:

$$F_{\mathrm{iv}} = 100 \times \frac{n_{\mathrm{iv}}}{N_{\mathrm{iv}}} \tag{4}$$

Here n_{iv} represents the number of months reaching the event threshold within each inland valley iv, while the total number of months in the study period provides the basis for calculating event frequency.

Following this, a Euclidean clustering analysis based on event duration, frequency, and residents' perceptions was conducted to categorize the inland valleys according to the predominant hazard (drought or flood). This clustering approach groups inland valleys that exhibit similar patterns of hazard occurrence, allowing for a nuanced classification of areas more prone to drought or flood conditions.

Temporal Analysis Based on SPEI 12-month Scale

Years were classified according to their SPEI values on a 12-month scale, allowing us to distinguish between periods with varying moisture conditions. Following this classification, we applied the non-parametric Mann-Kendall test to detect any significant trends over the years by using the pyMannKendall package (Hussain and Mahmud 2019). The Mann-Kendall test is instrumental here, as it does not assume a particular data distribution, making it well-suited for identifying gradual changes in climate data over time. This approach helped us observe whether there is a consistent trend in drought or flood occurrences, providing insights into potential shifts in climate patterns in the region.

Assessment of Mitigation Measures

An assessment was conducted to determine the frequency of adoption of various flood and drought mitigation measures. A correlation analysis explored potential relationships between these different mitigation strategies. Following this, the measures were categorized into three key usage groups: agricultural practices, ecological restoration measures, and infrastructure and technology measures.

Finally, Poisson logistic regression was applied to examine the potential drivers behind the probability of adopting several measures within each category. Each measure category is the dependent variable, a counting factor for the number of measures adopted, and the socioeconomic parameters are the independent variables. This approach provided insights into factors influencing the choice of mitigation strategies, helping to understand better how and why certain practices are implemented in response to flood and drought hazards.

Results

Spatiotemporal Analysis of Drought and Flood Occurrence

This section assessed the spatial and temporal occurrence of flooding and drought based on data from 1991 to 2021, as described in the methods.

Spatial Analysis of Drought and Flood Occurrence

The spatial analysis of flood and drought events occurring in the Savalou region over the last three decades is illustrated in Fig. 1. The analysis of this figure reveals that between 1991 and 2021, the region experienced flood events lasting between 4 and 7 months. Areas in the southeastern part of Savalou show a particularly prolonged flood duration, reaching up to 7 months in some instances compared to the northern part (see Fig. 1). Flood frequency varies from 19% to 37%, with a higher prevalence in the central and southeastern areas of Savalou, highlighting these zones as more frequently affected (see Fig. 1).

Regarding droughts, the analysis of Fig. 1 indicates that the inland valleys across Savalou generally experience drought events lasting between 4 and 10 months. The northern and eastern parts of the commune exhibit the most intense drought

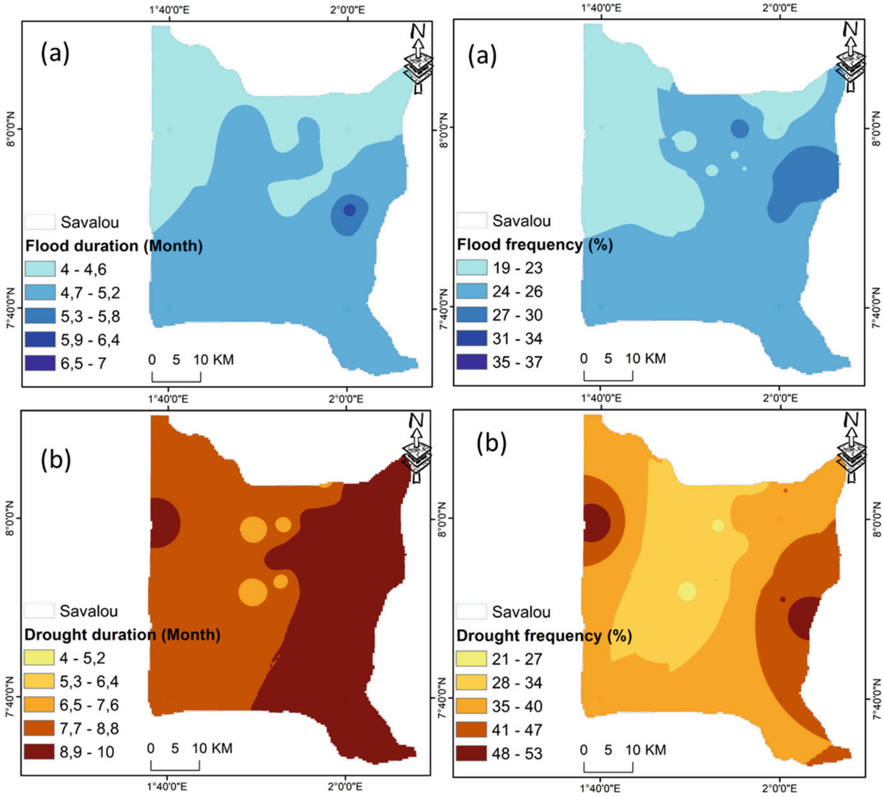

Fig. 1 Spatial analysis of (**a**) flood and (**b**) drought occurrences in Savalou, derived from data spanning 1991 to 2021. (Source: Own figure)

conditions, with events extending from 9 to 10 months, signifying a substantial vulnerability to prolonged arid conditions, as shown in Fig. 1. Furthermore, the frequency of drought episodes in Savalou can reach up to 53%, particularly concentrated in the northeastern part of the region (Fig. 1).

Temporal Analysis of Drought and Flood Occurrence

A temporal analysis of flood and drought occurrences in the Savalou commune (Fig. 2) reveals significant climatic variability, characterized by alternating wet and dry years over the past three decades. This fluctuation includes notable drought episodes in 1993, 2001, and 2016, alongside periods of moderate to severe wetness in 1991, 2008, 2009, and 2019. The years 1991 and 2019 stand out for their extremely wet conditions (SPEI > 1.5), while 2001 is identified as a year of severe drought (SPEI < -1.5).

Further cluster analysis (Table 1) identified two main clusters: 59% of the inland valleys in this commune are dominated by drought events with an average duration of 9 months and an average frequency of $42.61 \pm 4.23\%$. The second cluster is

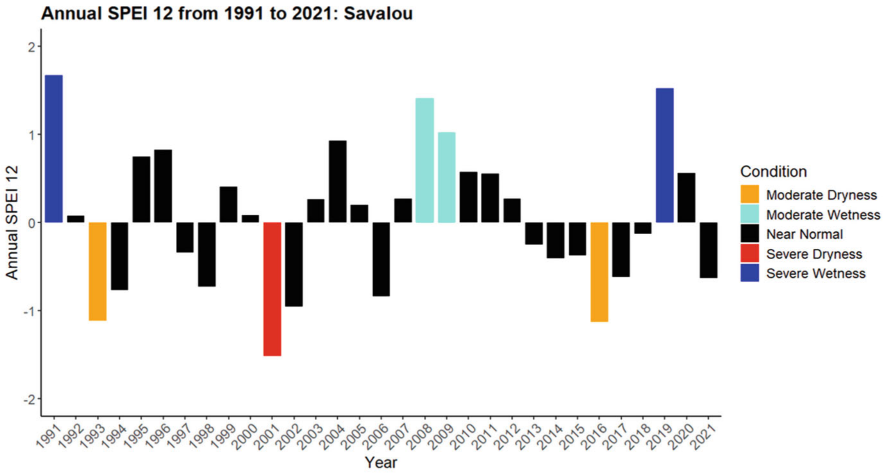

Fig. 2 Temporal analysis of the occurrence of floods and droughts in the Savalou commune from 1991 to 2021. (Source: Own figure)

Table 1 Hierarchical clustering for inland valleys with similar climatic hazards, based on duration and frequency of climatic hazards. (Source: Own table)

	Drought dominated IV	Flood dominated IV
Proportion	59%	41%
Flood duration (month)	4 ± 0.00	5 ± 0.3
Flood frequency (%)	20.60 ± 0.00	24.46 ± 2.95
Drought duration (month)	9 ± 0.00	7 ± 0.00
Drought frequency (%)	42.61 ± 4.23	27.39 ± 0.00

characterized by flood-dominated inland valleys (41%) with an average flood frequency of 24.46 ± 2.95% and an average flood duration of 5 ± 0.3 months (See Table 1).

Drought and Flood Mitigation Measures Adopted

During the field survey, three primary measures were globally reported by smallholder farmers:

(i) *Agricultural Practices:* According to Fig. 3, we noted that smallholder farmers reported adopting organic farming practices, including using organic manure at specific times. They also adjusted cropping seasons to align with periods of lower climate impact based on observations from previous years. Additionally, they adopted hybrid crop varieties that are more resilient, with some varieties

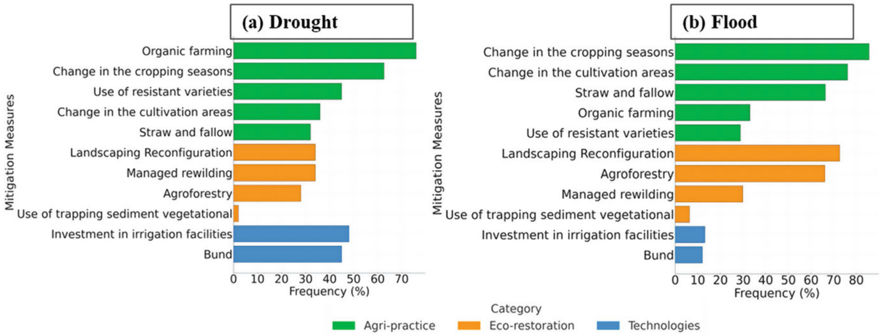

Fig. 3 Mitigation measures adopted for (**a**) drought and (**b**) flood conditions by category (*Agri-practices: Agricultural practices; Eco-restoration: Ecological restoration measures and Technologies: Infrastructure and Technology measures*). (Source: Own figure)

being early maturing to shorten the growing cycle or varieties that can adapt to the additional water level. Faced with the difficulties of controlling flood conditions, some farmers have opted to modify cultivated areas to mitigate hazards, especially inland valleys close to watercourses (Fig. 3b). This category of measures has a high adoption rate of 48% for drought and 46% for flood events.

(ii) *Ecological Restoration:* Smallholder farmers adopted approaches to reconfigure water flow pathways for better management, and some of them reduce the weed clearing around farms to control water flow (using vegetation to trap sediment) (Fig. 3). Some farmers also reported establishing buffer zones (strips of natural vegetation) around fields and along ditches. Moreover, some farmers utilized *Acacia* and *Eucalyptus* species around their farms to regulate water flow—an approach learned from the PACER project. Others mentioned using *Moringa oleifera* and *Mucuna* species along the boundaries of the inland valley based on the training they received from the PROSOL project. The adoption rate of this measure category is 19% for drought and 32% for flood events (based on survey data).

(iii) *Technological Development Measures*: Farmers sometimes installed irrigation systems based on bunds, such as smart valleys and procas (2 cases), and drains and wells to control water flow more effectively (Fig. 3). The adoption rate of this measure is 33% for drought and 22% for flood (based on survey data).

Figure 3 displays the frequency of different mitigation measures employed for drought (Fig. 3a) and flood (Fig. 3b) events.

In response to drought, the most frequently used measures include organic farming and change in the cropping seasons, both falling under the agricultural practice category, highlighting a solid reliance on agricultural methods (see Fig. 3).

Measures like managed rewilding and landscaping reconfiguration represent moderate usage under Ecological restoration. For flood hazards, changes in the cropping seasons and the cultivation areas are prominent, indicating the importance of adaptive agricultural techniques (see Fig. 3b). Ecological restoration measures, particularly landscaping reconfiguration and agroforestry, are also widely adopted for flood management, emphasizing the need for ecological adaptation in mitigating flood impacts.

The correlation results (Fig. S1) further reveal that, for flood mitigation, changes in the cropping season are positively correlated with changes in cultivation area, while bund establishment is positively correlated with landscaping reconfiguration ($r = 0.34$) and negatively correlated with agroforestry ($r = -0.35$). In drought mitigation measures, the use of straw and fallow shows a notable positive correlation with the practice of organic farming ($r = 0.45$) and landscaping reconfiguration ($r = 0.45$).

Determinants of Drought and Flood Adaptation Strategies

This section of the study presents the results of the Poisson regression model, which evaluates the likelihood that flooding or drought is perceived as a climatic hazard and assesses the probability that smallholder farmers adopt a certain number of mitigation measures across different categories. These probabilities are displayed in Table 2.

The results of this regression reveal that factors such as the distance of inland valleys (IV) from markets and roads, as well as the sources of seed and input acquisition, decrease the number of agricultural practices adopted to mitigate drought. For example, an increase of 1 km in the distance from the market relative to the IV is associated with a significant reduction of 5% in the number of agricultural practices adopted to combat drought. Similarly, the number of infrastructure and technology measures adopted to address drought decreases by 9% and 1% for each unit increase in distance to the nearest road and the number of input acquisition sources. Farmers who own inland valleys tend to more readily adopt more infrastructure and technology measures in response to drought. Additionally, membership in a farming organization is associated with a 36% increase in technology measures and a 1.5% increase in ecological restoration measures adopted in response to drought.

Regarding flooding, membership in a farming organization significantly increases the number of agricultural practices adopted. Furthermore, the quality of access roads (paved roads) and support from external institutions lead to respective increases of 61% and 109% in adopting infrastructure and technology measures. Finally, membership in a farming organization and support from external institutions are particularly associated with increases of 32% and 8%, respectively, in the number of ecological restoration measures adopted.

Table 2 Poisson regression analysis of determinants influencing the number of adopted measures for flood and drought mitigation. (Source: Own table)

Variable	Drought mitigation measures			Flood mitigation measures		
	Agricultural practice	Infrastructure technology	Ecological restoration	Agricultural practice	Infrastructure technology	Ecological restoration
	Estimate (Std. Error)	*Estimate (Std. Error)*	*Estimate (Std. Error)*	*Estimate (Std. Error)*	*Estimate (Std. Error)*	*Estimate (Std. Error)*
Intercept	**0.62 (0.58)***	−22.41 (0.45)	0.79 (0.51)	−0.20 (0.84)	**−0.16 (0.79)***	0.16 (0.58)
Distance from IV to road (Km)	**−0.05 (0.018)****	**0.09 (0.04)****	0.01 (0.01)	−0.02 (0.02)	0.04 (0.03)	0.045 (0.02)
Distance from IV to market (Km)	**−0.05 (0.014)****	−0.15 (0.05)	−0.02 (0.01)	−0.003 (0.017)	−0.005 (0.02)	−0.01 (0.01)
Percentage of women in the IV	0.002 (0.003)	0.01 (0.08)	–	0.003 (0.007)	−0.003 (0.009)	0.012 (0.006)
Source of seeds and inputs (Km)	**−0.04 (0.002)*****	**−0.01 (0.001)***	–	0.01 (0.02)	−0.05 (0.03)	−0.01 (0.02)
Quality of road to market: Asphalt Road	0.23 (0.46)	–	−0.08 (0.33)	1.32 (0.89)	**2.09 (0.12)***	0.20 (0.32)
Land ownership: Individual	0.10 (0.16)	**0.39 (0.36)***	0.03 (0.15)	0.26 (0.27)	0.47 (0.38)	0.13 (0.25)
Origin of IV users: Native	−0.15 (0.03)	0.16 (0.64)	0.08 (0.25)	0.80 (0.76)		0.36 (0.41)
Exploitation mode: Individual	0.30 (0.15)	0.52 (0.41)	0.16 (0.15)	−0.18 (0.25)	−0.13 (0.31)	0.26 (0.23)
	0.08 (0.13)	**0.36 (0.31)***	0.05 (0.13)	0.29 (0.21)	**0.61 (0.3)****	**0.32 (0.19)***

(continued)

Table 2 (continued)

Variable	Drought mitigation measures			Flood mitigation measures		
	Agricultural practice	Infrastructure technology	Ecological restoration	Agricultural practice	Infrastructure technology	Ecological restoration
	Estimate (Std. Error)	*Estimate (Std. Error)*	*Estimate (Std. Error)*	*Estimate (Std. Error)*	*Estimate (Std. Error)*	*Estimate (Std. Error)*
Received support from institution						
Member of farmers' organization	0.11 (0.13)	0.49 (0.34)	**0.015 (0.13)***	**1.74 (0.39)*****	0.19 (0.36)	**0.08 (0.25)***
Role of crop farming in the production system: Secondary role	0.06 (0.23)	–	0.03 (0.3)	0.01 (0.62)	0.60 (0.89)	0.04 (0.61)
	LR $chi^2 = 38.08$; Prob > $chi^2 = 0.0002$; Log-Likelihood = −205.96	LR $chi^2 = 6.99$; Prob > $chi^2 = 0.08$; Log-Likelihood = −81.50	LR $chi^2 = 12.08$; Prob > $chi^2 = 0.07$; Log-Likelihood = −202.87	LR $chi^2 = 51.73$; Prob > $chi^2 = 0.0003$; Log-Likelihood = −79.94	LR $chi^2 = 18.57$; Prob > $chi^2 = 0.03$; Log-Likelihood = −62.21	LR $chi^2 = 15.21$; Prob > $chi^2 = 0.08$; Log-Likelihood = −82.87

NB: Std.Error = Standard errors. * Significant at 10% ($p \leq 0.1$). ** Significant at 5% ($p \leq 0.05$). *** Significant at 1% ($p \leq 0.01$)

Discussion

Spatiotemporal Occurrence of Flood and Drought

The study identified a recurring pattern of alternating years of drought and flooding in the inland valleys of Savalou (Fig. 2), which aligns with two significant observations. First, this pattern corroborates the perceptions of smallholder farmers who report a repeated cycle of droughts and floods occurring approximately every 2 years. This cyclical phenomenon complicates the implementation of mitigation strategies and reinforces the challenges faced by agricultural communities. Secondly, the findings are consistent with the broader climatic variability attributed to the Sudano-Guinean zone of Benin, where precipitation patterns are increasingly unpredictable and extreme (Saïdou et al. 2018). For example, the temporal distribution shown in Fig. 2 highlights recurrent periods of both moderate to severe dryness (e.g., 1992, 1999, 2017, and 2021) and extreme wetness (e.g., 1991, 2008, 2009, and 2019) in Savalou between 1991 and 2021. This alternating pattern underscores the intensification of climatic extremes, complicating the region's water resource management and agricultural planning. Such climatic behavior is characteristic of regions influenced by multiple factors, including local topography, large-scale atmospheric circulation, and evolving land use patterns, all of which drive climatic variability (Dossou-Yovo et al. 2019).

The alternating cycles of drought and flooding may suggest the involvement of climatic mechanisms such as the El Niño-Southern Oscillation (ENSO) or localized climate drivers, including land-atmosphere interactions and seasonal shifts. Research in comparable regions has demonstrated that phenomena like ENSO, linked to fluctuations in sea surface temperatures, can significantly alter precipitation regimes, resulting in alternating periods of extreme dryness and wetness (Han et al. 2019; Salack et al. 2014). The complex topography of the inland valleys of Savalou further exacerbates these dynamics. These valleys, functioning as lowland floodplains, are natural catchment areas that experience severe flooding during periods of high rainfall (see Fig. 1 for example) due to water accumulation (Hector et al. 2018). Conversely, during years of reduced rainfall, these areas are prone to drought (see Figs. 1 and 2 for example), driven by limited water inflow and elevated evaporation rates. Studies on West African inland valleys, such as those by (Hector et al. 2018), reveal that these environments are particularly vulnerable to climate extremes, and their poor water retention capabilities often amplify the impact of alternating drought and flooding events. These prolonged droughts, followed by sudden floods, disrupt the natural hydrological cycle, devastating the region's ecosystems and socioeconomic systems. The compounded effects of these extremes highlight the urgent need for adaptive strategies tailored to the inland valleys' unique climatic and geographic challenges.

The study also highlighted frequent and prolonged droughts in the eastern and northern parts of the commune (see Fig. 1), contrasting with high concentrations and long durations of flooding in the southern region compared to the northern region (see Fig. 1). This observation may be linked to the inland valleys trending southward, which are slightly influenced by the Guinean climate, known for its higher precipitation and humidity levels. In contrast, the northern climate may influence areas farther north, which is marked by reduced precipitation distribution (Lokonon 2017). This finding aligns with the broader study of drought and flood occurrences across Africa by Ekwezuo and Ezeh (2020), who initially linked the higher frequency of flooding in southern regions compared to the north to the effect of a moist monsoon on rainfall distribution. Additionally, Dossou-Yovo et al. (2019) reported that local environments near oceanic zones are more susceptible to humidification effects from increased sea evaporation driven by rising sea temperatures. This phenomenon may also explain the wetter and more frequent flooding in the inland valleys of South Savalou, which are closer to Benin's coast than northern areas. Bonou et al. (2024) similarly associated the occurrence of inland valley floods with proximity to rivers and water bodies.

In particular, moderate and severe flooding observed in 1992, 2008, 2009, and 2019 (see Fig. 2) highlights the increasing frequency of these events in recent decades, underscoring the need for appropriate measures. For instance, from 2009 to 2010, several studies have reported that Benin experienced a severe flood that paralyzed many economic services and significantly impacted the agricultural sector (Bonou et al. 2024; World Bank 2011). According to Bonou et al. (2024), these events pose a potential threat, especially to rice paddies, calling for proactive measures. The findings underscore the urgent need to implement measures tailored to each inland valley's hazards.

The study revealed that drought poses a significant hazard, impacting 53% of the inland valleys surveyed (see Table 1), thereby emphasizing its prevalence as a critical stressor in the region. This observation aligns with the climate projections of Ahmed (2020), which forecast a marked increase in drought events across African ecosystems by 2060, with agriculture projected to suffer an estimated 40% reduction in crop yields. Dossou-Yovo et al. (2019) and Diagne et al. (2013) identified drought as the most pressing stressor for inland valleys in sub-Saharan Africa, affecting over 38% of these ecosystems. According to Dossou-Yovo et al. (2019), this vulnerability is shaped by key predictive factors such as the water retention capacity of the valleys, precipitation levels, the Standardized Precipitation-Evapotranspiration Index (SPEI), and other localized determinants that warrant further investigation. These findings highlight the complexity of drought impacts in inland valleys and the critical need for site-specific research to inform adaptive strategies and mitigate the escalating effects of climatic extremes.

Mitigation Measures and Indicators for Adoption

Smallholder farmers adopt various strategies to address climatic hazards, employing diverse measures that span agricultural practices, technological investments, and ecological restoration efforts (see Fig. 3 and Fig. S1). These observations align with extensive research highlighting the reliance on localized approaches by smallholders in developing climate hazard management strategies (Bonou et al. 2024; Dossou-

Yovo et al. 2019; Nemine 2015). Notably, studies reveal the frequent use of farming practices, such as drought-resistant crop varieties, and agricultural technologies like bund systems to mitigate drought effects (see Fig. 3a). This finding is consistent with Dossou-Yovo et al. (2019), who reported widespread adoption of short-duration, drought-resistant varieties in the inland valleys of the Sudan-sahel region of Africa. Furthermore, research by Dossou-Yovo et al. (2022) underscores the pivotal role of agricultural research institutions like AfricaRice Center in developing and disseminating water management technologies and agronomic practices over the past three decades. AfricaRice Center initiatives, including "Smart-Valleys" and SAWAH technologies, significantly influence smallholders' preferences. For instance, the "Smart-Valleys" approach, introduced in Benin and Togo in 2012, focuses on improving water and soil management while enhancing inland valley productivity (Akodekou et al. 2024). This method, widely adopted across West Africa, is notably utilized by farmers in Savalou who participated in SMART-VALLEY training programs to conserve soil moisture and optimize water use (Arouna and Akpa 2019).

In parallel, smallholder farmers primarily focus on developing agricultural practices like flood-resistant crop varieties and ecological measures like agroforestry to manage flooding (see Fig. 3a). These findings are consistent with studies on flood hazard management in flood-prone areas (Sahoo and Prasad 2024; Bairagi et al. 2021; Bonou et al. 2018; Nemine 2015). For example, Bangladeshi farmers adopt flood-tolerant rice varieties such as Sub1 and utilize water control technologies during flooding. Similarly, in Asia, Sahoo and Prasad (2024) report the widespread use of integrated agroforestry systems, such as combining sugar palms with rainfed rice (RLR-SP), as effective flood management strategies. In Nigeria, farmers rely on indigenous knowledge, employing flood-resistant plant varieties and establishing resilient plants on their farms to mitigate flooding impacts (Nemine 2015).

However, Dossou-Yovo et al. (2019) note that the farmers' socioeconomic conditions often influence the adoption of such measures.

Socioeconomic factors, including access to farmer organizations and external institutional support, proximity to markets and roads, and financial resources, play a crucial role in shaping smallholders' ability to adopt these measures in our study area (see Table 2). Studies by Bonou et al. (2024) and Dossou-Yovo et al. (2019) highlight that smallholder farmers in West Africa, who frequently face financial constraints, are often limited in their capacity to implement effective drought and flood mitigation strategies due to these socioeconomic barriers.

The study revealed, for example, that farmers farther from access roads and agricultural product markets adopt fewer agricultural practices (see Table 2). Financially limited smallholder farmers often avoid investing heavily in fuel for drought management measures (see Table 2). Additionally, smallholders who own their inland valleys are more likely to increase the number of valley development measures (see Table 2). According to (Dossou-Yovo et al. (2019) and Yegbemey et al. (2013), smallholders prefer to secure land ownership or have the option to purchase inland valleys before implementing drought management measures.

Regarding flooding, the results indicate that the number of agricultural practices adopted increases with road quality, membership in farmer organizations, and support from external institutions (see Table 2). Knowledge and development of new inland valley management practices have been made possible through the involvement of several support institutions, such as PROSOR, AFRICARICE, ATDR, and PACER, as reported by smallholders who typically belong to farmer organizations like the *Union Communale des Riziculteurs* (UCR), IFEDUN, FINFONME, SENA, MISSOGBE, GBEDOKPO, and TOGBE. Generally, when projects are implemented at the commune level, only farmers belonging to these organizations receive information and support on newly adopted approaches.

These findings highlight the importance of institutional support through training, improved farm access roads, and farm security for smallholders in managing flood and drought hazards.

Conclusion

This study investigates the distribution of flood and drought hazards, the mitigation measures implemented, and the factors influencing smallholder farmers' adoption of these strategies in the inland valleys of Savalou. Analyzing historical climate data alongside survey results, the research reveals that the southern region of Savalou is more prone to flooding, while the northern region faces greater vulnerability to drought. This insight can inform hazard monitoring efforts in these inland valleys and guide public policy. Nonetheless, incorporating additional parameters related to the physical characteristics of the valleys would enhance the understanding of the indicators contributing to these hazards in the studied areas.

The most frequently adopted drought mitigation measures are primarily agricultural practices, including the selection of drought-resistant and resilient crop varieties, organic farming techniques, and the use of agricultural technologies to counter drought conditions. For flood management, farmers prefer practices such as cultivating flood-resistant crop varieties and engaging in agroforestry. However, there is a notable gap in information regarding the medium- and long-term effectiveness of these measures, suggesting that a more detailed investigation could shed light on their sustained efficacy.

The study also identifies several socioeconomic factors that impact the adoption of mitigation measures. Proximity to input markets, institutional support, and land ownership are critical for drought mitigation, while membership in farmer organizations and institutional backing play significant roles in flood mitigation.

The recommendations from this study advocate for customized approaches reflecting the varying severity of hazards within inland valleys. Empowering smallholder farmers is essential and can be effectively supported by external institutions. Research organizations should prioritize developing locally adapted crop varieties, while project institutions can facilitate knowledge sharing and promote farmer organization membership. State institutions are encouraged to implement policies that secure farmers' land tenure and resources, establishing a solid foundation for long-term resilience.

Ultimately, this study underscores the necessity for further research into the key predictors of these hazards and a thorough evaluation of the medium- and long-term effectiveness of current mitigation measures. Addressing these gaps will better equip smallholder farmers to manage climate hazards, promoting sustainable and resilient agricultural practices in the inland valleys.

Author Contribution All authors were actively involved in the study's conceptualization and design. Abiola David AKODEKOU played a central role in data collection, analysis, interpretation, and manuscript preparation. Kolawolé Valère SALAKO and Elliott Ronald DOSSOU-YOVO significantly contributed to data analysis, interpretation, and the manuscript's writing. Sabaké Tianegue DIARRA, Udo NEHREN, and Romain GLELE KAKAÏ provided comprehensive revisions to ensure the study's accuracy and clarity.

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