Flood risk assessment and adaptation under changing climate for the agricultural system in the Ghanaian White Volta Basin

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Abstract

In the context of river basins, the threat of climate change has been extensively studied. However, many of these studies centred on hazard analysis while neglecting the need for comprehensive risk assessments that account for exposure and vulnerability. Hazard analysis alone is not adequate for making adaptive decisions. Thus, to effectively manage flood risk, it is essential to understand the elements that contribute to vulnerability and exposure in addition to hazard analysis. This study aims to assess flood risk (in space and time until the year 2100) for the agricultural system, in the White Volta Basin in northern Ghana. Employing the impact chain methodology, a mix of quantitative and qualitative data and techniques were used to assess hazard, exposure, and vulnerability. Multi-model climate change data (RCP 8.5) from CORDEX and observation data from the Ghana Meteorological Agency were used for hazard analysis. Data on exposure, vulnerability, and adaptation were collected through structured interviews. Results indicate that flood hazard will increase by 79.1% with high spatial variability of wet periods but the flood risk of the catchment will increase by 19.3% by the end of the twenty-first century. The highest flood risk is found in the Upper East region, followed by North East, Northern, Savannah, and Upper West for all four analysed periods. Adaptive capacity, sensitivity, and exposure factors are driven by poverty, ineffective institutional governance, and a lack of livelihood alternatives. We conclude that the region is highly susceptible and vulnerable to floods, and that shifting from isolated hazard analysis to a comprehensive assessment that considers exposure and vulnerability reveals the underlying root causes of the risk. Also, the impact chain is useful in generating insight into flood risk for policymakers and researchers. We recommend the need to enhance local capacity and foster social transformation in the region.

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1 Introduction

Climate change is a major global challenge that poses a significant threat to societies and ecosystems worldwide (IPCC 2018, 2022). In West Africa, including Ghana, increased climate variability negatively affects the economic systems, particularly rainfed agriculture, due to poor water control and reservoir replenishment (Barry et al. 2018). According to Abban et al. (2021), agriculture accounted for about 20% of Ghana's GDP in 2019. The Ghana Statistical Service states in the 2017/18 Ghana Census of Agriculture that 37.5% of the population was engaged in agriculture in 2017 (Ghana Census of Agriculture 2020). The sector is vulnerable to climate risks, such as floods, drought, heavy precipitation, and land and soil degradation which adversely affect yields and livelihoods (Derbile et al. 2022; Derbile & Laube 2014). Flood hazards pose a significant threat to agriculture in the region, with their destructive nature, unpredictability, and negative impacts on livelihoods (Armah et al. 2010). Effective adaptation strategies are crucial for vulnerable agricultural systems in northern Ghana due to the high risk of climate change impacts and the lack of mitigation measures (Dolšak & Prakash 2018). Therefore, this study aims to evaluate flood risk to inform the adaptation of the agricultural system in the White Volta Basin.

Despite the White Volta Basin being a data-scarce region, multiple modelling studies have been conducted in the area. Many studies looked at streamflow responses, hydrology, or hydro-climatic changes under different climate scenarios for example Abubakari et al. (2018), Nyadzi et al. (2021a, b), and He et al. (2022). Some studies looked at the socio-economic impact of climate change (Abass et al. 2022; Amikuzuno 2018; Mensah & Ahadzie 2020; Musah et al. 2013; Yaro 2013). To the best of our knowledge at the time of this study, almost no research has been conducted on future climate change risks for agriculture by combining hazard, vulnerability, and exposure in the area. To manage flood risk, it is crucial to understand which parts of the system contribute to vulnerability and exposure and combine this with accurate hazard mapping.

This study assesses the risk of floods for the agricultural system in the White Volta Basin in northern Ghana, by applying the impact chain approach as described by Fritzsche et al. (2014) and GIZ and EURAC (2017). This method assesses hazard, vulnerability, and exposure separately using both quantitative and qualitative methods, and then combines them into a comprehensive risk assessment. Results can aid in climate change adaptation and climate service development. This research, therefore, addressed the question: To what extent is the agricultural system in the White Volta Basin of Ghana at risk of climate change-induced floods, analysed in terms of hazard, vulnerability, and exposure, and how does this change in time and space?

2 Conceptualising the impact chain framework

Traditional flood risk management approaches have been mainly focused on reducing the probability of flood hazard (Merz Aerts et al. 2014). However, over the past decades, the paradigm has shifted from the hazard-centred perspective to a broader risk-based perspective including social processes and implications. The Global Assessment Reports of the United Nations Office for Disaster Risk Reduction in 2011 defined risk as the interaction between hazard, vulnerability, and exposure (Merz Aerts et al. 2014; UNISDR 2011). The

IPCC adopted it later in the Fifth and Sixth Assessment Reports (AR5 & AR6). Figure S1 in the supplementary material shows how the concepts are interrelated (IPCC 2018, 2022).

Generally, risk is defined as "the potential for consequences where something of value is at stake and where the outcome is uncertain" (IPCC 2022). In the context of this research, risk refers to the risk of climate-induced floods on the agricultural system in the White Volta Basin. Climate-induced floods are defined as a hazard threatening a system. Hazard is defined as "the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources" (IPCC 2022). Within the system at risk, there are exposed elements that are susceptible to the hazard. These elements together form the exposure that a certain system has to a specific hazard. Exposure is defined as "the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected" (IPCC 2022).

Vulnerability relates to attributes within the exposed elements that potentially increase or decrease the consequences caused by the hazard (GIZ & EURAC 2017). Vulnerability is separated into two elements, sensitivity and capacity. Sensitivity relates to the factors that directly affect the consequences of hazard (GIZ & EURAC 2017). Capacity is the ability to cope with or adapt to the adverse consequences of hazard. Vulnerability is therefore defined as "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC 2022).

The impact chain methodology proposes a step-by-step risk assessment that is in line with the key concepts defined in the IPCC Fifth Assessment Report and was first published by Schneiderbauer et al. (2013) and later elaborated upon by Fritzsche et al. (2014). Impact chains consist of hazard, vulnerability, and exposure components with related factors and indicators. It systemises the components and factors that drive climate risk and their relationships with connecting arrows as shown in Fig. 1 (GIZ & EURAC 2017). The intermediate impacts illustrate the cause-effect chain leading to risk and are a function of both hazard and vulnerability factors.

3 Methodology

3.1 Description of the study area

The study was conducted in northern Ghana located in the white volta basin, bordered by Burkina Faso, Togo, and Cote D'Ivoire, and covers the area between latitudes 8°N and 11°N and longitudes 2.5°W and 0.5°E (Owusu & Klutse 2013). The area is divided into five administrative regions, namely Upper West, Upper East, North East, Northern, and Savannah, with regional capital towns of Wa, Bolgatanga, Nalerigu, Tamale, and Damango, respectively (Klutse et al. 2021) (Atanga & Tankpa 2021). The catchment in Ghana, which includes 30 districts, covering 50,000 km^2, represents about 20% of Ghana's land surface (WRC 2021). The White Volta River enters Ghana from Burkina Faso near the town of Bawku. Figure S2 in the supplementary material illustrates the study area and its regions.
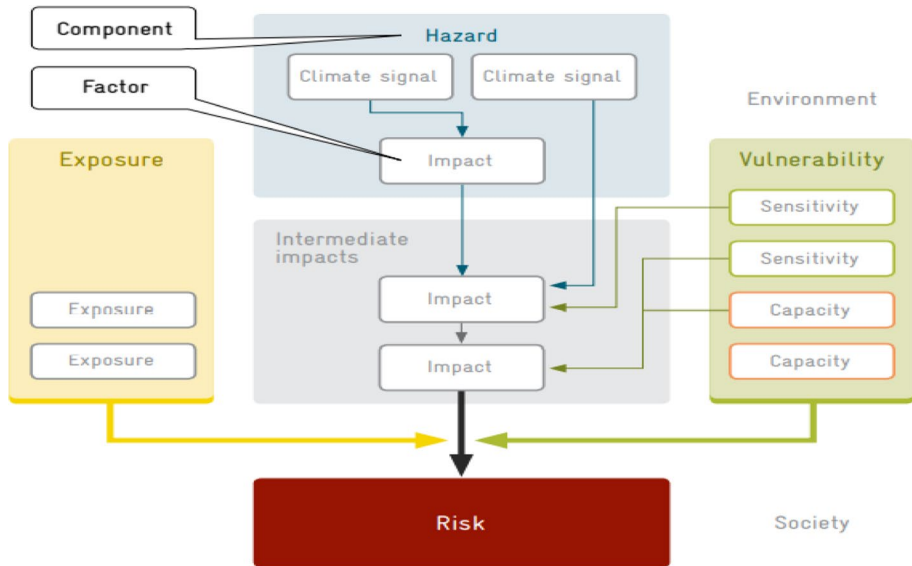
Fig. 1 Basic structure of an impact chain of climate risk for a certain system consisting of components and factors (GIZ & EURAC 2017)

The north of Ghana is divided into two agroecological zones, the north is the Sudan Savannah and the south is the Guinea Savannah (Bessah et al. 2021). The main soils in the catchment are Luvisol, Regosols, and Lithosols which cover about 70% of the catchment (Abubakari et al. 2018). Vegetation in the region is characterised by tropical savannah flora and fauna and contains grasslands and drought-resistant trees (Atanga & Tankpa 2021). The area has an unimodal rainfall season which starts between March and April and ceases by October (Aryee et al. 2018; Atanga & Tankpa 2021).

Annual rainfall is between 700 and 1050 mm (Atanga & Tankpa 2021). The temperatures vary between 15 and 40 °C annually, mainly driven by the harmattan seasonal winds blowing from the Sahara desert southward (Atanga & Tankpa 2021). The hottest period is between December and March. The mean annual evapotranspiration is around 1650 mm (Awotwi et al. 2015). Recent studies show an increase in precipitation in agricultural areas (Awotwi et al. 2015; Bessah et al. 2021). Especially during the rainy season, precipitation is expected to increase by 0 to 40% by the end of the century (Bessah et al. 2021).

Livelihood activities in the north of Ghana are dominantly dependent on the annual rainfall regime (Atanga & Tankpa 2021). About 60 to 77% of the population is engaged in rainfed agriculture which is the predominant source of livelihood (Antwi-Agyei et al. 2018; Bessah et al. 2021; Tahiru et al. 2020). Other livelihood activities include fishing, forestry, charcoal burning, stone quarrying, gold mining (locally called galamsey), and agro-industries (Tahiru et al. 2020). Besides this, traditional practices such as slash and burn and bush burning practices are still used widely, which lead to further degradation of soil and water resources in the basin (WRC 2021).

The Ghana Water Research Institute of the Council for Scientific and Industrial Research (CSIR-WRI) states that all river basins in Ghana are vulnerable to climate change, and reports a general reduction in annual river flow of 15 to 20% in 2020 already

and 30 to 40% decrease in 2050 (Kankam-Yeboah et al. 2011). This decrease is mainly linked to an increase in irrigation demands in rural areas in the future (Kankam-Yeboah et al. 2011). Studies show that households and farmers' areas of the White Volta Basin (Adomah Bempah & Olav Øyhus 2017) are among the highest vulnerable communities with the lowest adaptive capacity in the country (Almoradie et al. 2020; Antwi-Agyei et al. 2018, 2012; Atanga & Tankpa 2021; Braimah et al. 2014).

The catchment experiences almost annual floods which typically occur due to excessive precipitation in combination with spillage from the Bagre Dam in Burkina Faso (Armah et al. 2010). Once every couple of years, more destructive floods occur due to a combination of events, for example, a long dry spell followed by torrential rains and spillage at the Bagre Dam (Armah et al. 2010).

3.2 Data collection and analysis

3.2.1 Flood hazard analysis

Using the Standardised Precipitation Index (SPI), developed by McKee et al. (1993), SPI-3 values of separate months and a set of indicators were generated to function as a proxy for floods in the catchment using Eq. 1.

$$SPI_{ijk} = \frac{P_{ijk} - \overline{P}_{ij}}{\sigma_{ij}} \tag{1}$$

where SPI_{ijk} is the z-value for the pixel i during timeframe j for year k, P_{ijk} is the precipitation value for pixel i during period j for year k, P_{ij} is the mean for pixel i during timeframe j over n years, and σ_{ij} is the standard deviation of pixel i during week j over n years.

The SPI can monitor wetter periods as well as drought periods and represent them in a similar way (McKee et al. 1993; Guerreiro et al. 2007). Based on this, Seiler et al. (2002) and Guerreiro et al. (2007) first suggested it could also be used for analysing wetter than normal periods and flood monitoring. In this case, we use the averaging time scale of 3 months which correlates most with flood conditions occurring from extreme precipitation (Guerreiro et al. 2007). A SPI value above 1.0 gives a realistic chance for minor flood occurrences and an SPI > 1.5 for (severe) flood events.

Daily precipitation, maximum daily temperature (T_{max}), and minimum daily temperature (T_{min}) for RCP 8.5 at a resolution of 0.44° from the year 2006 till 2100 of the Coordinated Regional Climate Downscaling Experiment (CORDEX) were used. The data was sourced from three CORDEX models: RCA4-CCCma-CanESM2, RCA4-NCC-NorESM1-M, and REMO2009-MPI-M-MPI-ESM-LR. The models were chosen based on the positive performance assessment studies for CORDEX data in Africa as described by Ashaley et al. (2020); Mascaro et al. (2015); and Okafor et al. (2019). The data from these three models were extracted and remapped for the catchment area before they were combined to create an ensemble mean for each variable using Climate Data Operator (CDO). The analysis was performed for a five-time series of 16 years (for the historical set) and 20 years (future simulations):

- Historical period: from 2006 till 2020
- Period 1: from 2021 till 2040

- Period 2: from 2041 till 2060
- Period 3: from 2061 till 2080
- Period 4: from 2081 till 2100

For all grid cells in the catchment area, the centroid was determined, and each cell closest to the centre of one of the 30 districts was selected. The resulting 19 grid cells were used as a representation for the districts and used to perform the SPI analyses.

A gauged daily precipitation, T_{max} and T_{min}, from 1999 to 2018 at the Navrongo, Tamale, and Wa stations, was obtained from the Ghana Meteorological Agency (GMET). The three stations are located along the northern, south-eastern, and western border of the catchment. Using all three gauging stations provides a good cover of the whole catchment although more gauging stations would have been ideal for analysis. However, this was the only data available at the time. As a preliminary performance evaluation, a comparison was done for the aggregated CORDEX and gauged data for the study area for the years 2006 to 2018. The comparison between gauged and the CORDEX precipitation resulted in a correlation coefficient of 0.82 and R^2 of 0.67, suggesting a positive correlation between the two data sets; although this is an initial indication, it validates the use of the CORDEX ensemble mean data set.

Based on the SPI indicators, the hazard segment of the impact chain for flood risk was calculated. Prior to the SPI analysis, however, floods that occurred in the area between 1999 and 2018 were listed as documented by FloodList. The historical flood events were linked to the SPI values of the months during and before the event. Based on these events, a threshold was formulated for SPI values to function as a proxy for floods. This threshold aligns with thresholds for flood probability as described by Liu et al. (2018) and Guerreiro et al. (2007).

The flood hazard assessment is based on two indicators: too-high intensity of precipitation, and too-high cumulative precipitation. The indicators for these factors are the number of occurrences of an SPI value higher than 1.5 and the number of occurrences of three consecutive SPI values higher than 1.0. Combining these two using the aggregation method, as discussed in Sect. 3.2.4, led to the hazard assessment for the five time periods per district. This was then spatially mapped using GIS software.

3.2.2 Exposure and vulnerability analysis

To identify and assess the factors and indicators of flood exposure and vulnerability, eight interviews were conducted with representatives from different administrative levels of government as well as with different research institutes in Ghana involved in flood and water management in the White Volta Basin. Representatives from the following institutions were interviewed:

- Hydrological Services Department
- National Disaster Management Organisation (NADMO)
- Land and Water Management Unit of the Crop Services Department of the Ministry of Food and Agriculture

- Tamale Metropolitan Assembly Agric Department, part of the Ministry of Food and Agriculture
- CSIR Water Research Institute, Tamale Office
- University for Development Studies, Department of Environment, Water, and Waste Engineering
- University of Development Studies, and WACWISA
- Water Resources Commission, and WASCAL

The questionnaire for the interviews was semi-structured with open-ended questions designed to focus on the depth of the discussions rather than the number of respondents. The interview consisted of four sections, and each lasted an average of 90 min: introduction, exposure, vulnerability, and future outlook. The introductory questions established flood consequences for agriculture and their future changes, which informed the impact chain's intermediate impacts. In the exposure and vulnerability sections, interviewees rated levels of exposure, sensitivity, and adaptive capacity using a land cover/use map from the European Space Agency (Figure S3 in the supplementary material). Exposure, sensitivity, and adaptive capacity factors were also identified and rated on a score of 1 to 10 to be used as input for the quantitative analysis. The interviews concluded with questions on future societal change and how the government can reduce future flood risk for agriculture. Simple descriptive statistics were used to analyse interview results, which were supplemented with literature research to explain the factors and indicators in the exposure and vulnerability impact chains.

3.2.3 Impact chain indicators

Guidelines from GIZ & EURAC (2017) were used alongside the interviewees' identified factors to select factors for exposure and vulnerability. The guiding question for vulnerability was "Which attributes of the system contribute to the risk?" The guiding question for sensitivity was "Which attributes make the system vulnerable to potential negative impacts of the hazard(s) under consideration?", and the question for capacity was "Which abilities of the societal system are in place or missing to reduce the risk of concern—now and in future?" The identified factors were linked in the impact chain to the intermediate hazards, which have been identified based on the interviews.

3.2.4 Composite flood risk

The separate assessments of hazard, vulnerability, and exposure were combined into one comprehensive aggregated assessment of flood risk for agriculture following Fig. 1. A combined impact chain from the results of the three sub-assessment needs was created. This interlinks all factors, indicators, and intermediate impacts related to hazard, vulnerability, and exposure to the risk of climate change-induced floods. The quantitative results of hazard, exposure, and vulnerability were normalised and aggregated into the risk component. For the aggregation, a "weighted arithmetic aggregation" method was used, because it leads to full compatibility (Commission 2008). The calculation of the composite risk was done for each of the 30 districts in the catchment and all four time periods.

4 Results

4.1 Changes in SPI and occurrence of floods

Results of the literature search show that seven unprecedented floods occurred in the study area from 1999 to 2019 (Table 1) (FloodList 2022). Relating the SPI results to historical floods shows that flood occurring months did not correspond to high SPI values, yet a better picture was found when 2 months before the event was considered. Table 1 shows that at least once in 2 months before the flood, a month with an SPI > 1 occurred. Also, severe floods occurred when SPI is above 1.5. Five of the flood events that occurred 2 months earlier show negative SPI values. For a flood event to occur, extreme precipitation can take place at local scales and does not necessarily cover the whole catchment. Results also show that the mean SPI values of the catchment are quite low, as you would expect with high spatial variability.

The SPI values > 1.5 together with cumulative precipitation form the indices to calculate flood hazard (Figure S4 in the supplementary material). SPI values > 1.5 in the study area for the historic period till period 4 are 194, 297, 287, 263, and 277, respectively. After a steep increase in the post-historic period, they slightly decrease and then stabilise in periods 3 and 4.

The cumulative precipitation exhibits a different trend in SPI occurrences. In the overall 19 data points per period, the total occurrences of three consecutive months with an SPI value > 1.0 are 63, 86, 88, 86, and 111 for the historic period till period 4. The occurrences show a steep increase in the first 20 years after the historic period, followed by a stable period of 40 years, and then another steep increase until 2100. Overall, the occurrences of SPI > 1.0 in three consecutive months increased by 76.2% compared to the historical series. Furthermore, the study found that monthly maximum SPI values increased by 8.42% on average between 2006–2020 and 2080–2100, with up to a 24.5% increase during only the rainy months.

The composite flood hazard based on normalised SPI > 1.5 occurrences and normalised occurrences of three consecutive wet months is shown in Fig. 2. There is an increase in hazard towards the end of the century, with some spatial variability. Almost all districts experienced heightened flood hazard except for those in the Upper West region and most downstream districts. The total increase in flood hazard compared to the historical period is 79.1%. The results indicate a spatial concentration of high SPI values, consistent with historical flood events where high SPI values, leading to floods, were often observed at one of the three locations.

4.2 Climate change and flood impact on agriculture

The expected changes in climate, their effects on agriculture, and the frequency of mention by interviewees are presented in Figure S5 of the supplementary material. The key identified climatic changes in the study area and their frequency of mention are (i) an increase in flood (100%), (ii) an increase in drought (75%), (iii) a shift in the start and end of the rainy season (50%), (iv) an increase in variability of precipitation (50%), (v) an increase in the intensity of precipitation (25%), and (vi) an increase in the spatial distribution of precipitation (25%). The expected increase in the intensity of precipitation can increase discharge and flood risk for agriculture. According to the respondents, increased intensity of rainfall

Table 1 Overview of flood history, and number of people affected in the catchment (FloodList 2022) and SPI values (author's construct)

Year	Navrongo			Tamale			Wa			Average SPI in the catchment	Max SPI in the catchment	# of people affected
	SPI 2 months before flood	SPI 1 month before flood	SPI during flood month	SPI 2 months before flood	SPI 1 month before flood	SPI during flood month	SPI 2 months before flood	SPI 1 month before flood	SPI during flood month			
2007	1.0	1.8	1.5	−0.4	−0.4	0.7	0.0	−0.8	−1.1	0.2	1.8	332,600
1999	1.2	2.1	2.9	1.9	1.6	1.6	1.0	1.0	1.3	1.6	2.9	291,573
2009	−0.5	−0.3	−0.5	0.2	0.1	0.7	1.0	0.9	0.3	0.3	1.0	139,700
2010	0.3	0.3	1.2	0.8	0.7	1.6	−0.1	0.3	0.4	0.6	1.6	34,826
2018	−0.7	0.8	0.8	1.2	1.0	−1.3	0.6	0.4	1.4	0.5	1.4	31,903
2019	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	26,083
2013	1.0	1.6	0.3	1.0	0.6	1.8	−0.1	1.6	2.1	1.1	2.1	25,000
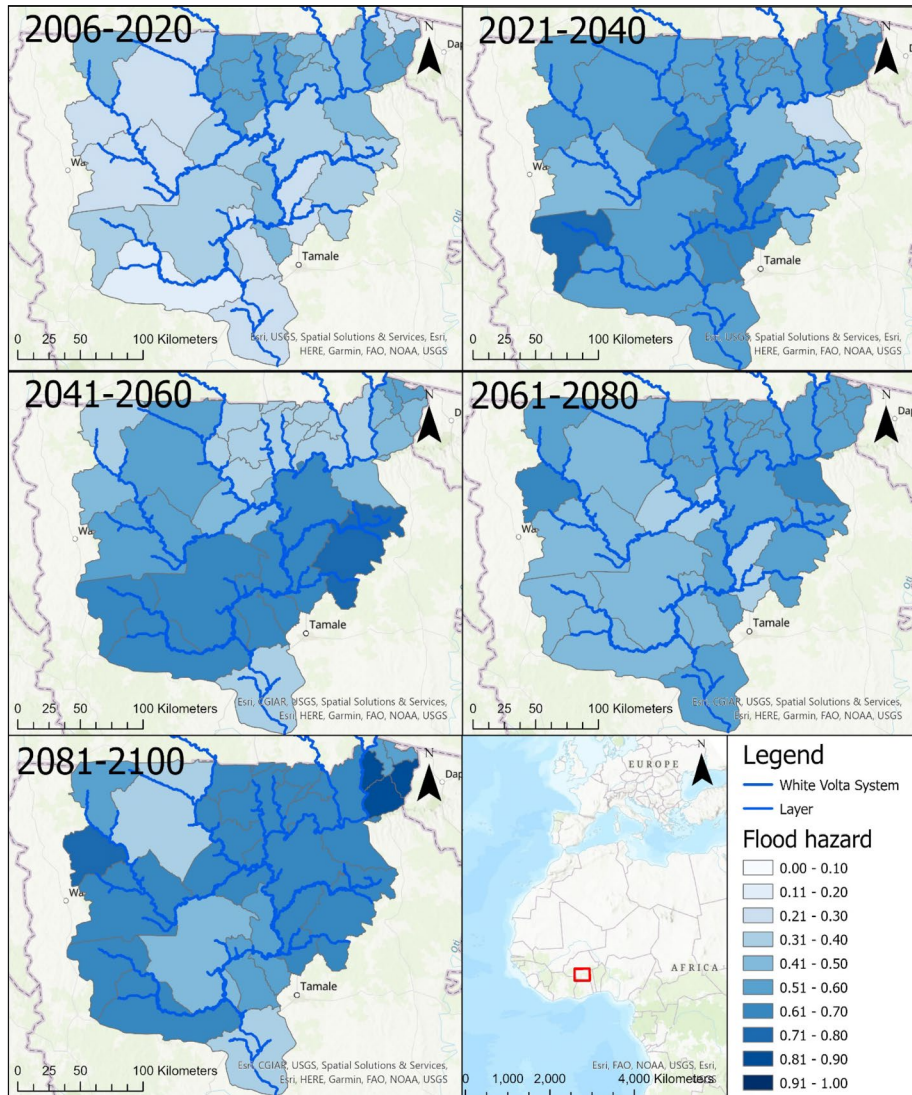
Fig. 2 Flood hazard map, depicted on a normalised scale where 0 represents that the region does not experience hazard and 1 represents that the region experiences critical levels of hazard

will cause more erosion and transportation of sand, silt, waste materials, and other debris. This increases the siltation downstream causing the river bed to heighten leading to less capacity which increases the flood risk.

The change in rainfall variability impacts the start of the rainy season, which has shifted almost a month later and has become more erratic. However, only farmers in the floodplains are most impacted, while farmers in upland areas and those farming after the rainy season are less affected. Farmers in floodplains plant early maturing-variety crops like maize after the first rains (March–April) and usually harvest by June before floods occur.

However, changes in rainfall patterns make it difficult to estimate the onset of rains, leaving farmers at risk of early drought or later floods. Farmers in upland areas start farming later, using the later rains in June-July, and are less exposed due to their location. The third group of farmers waits till the end of the rainy season in October to use antecedent soil moisture to cultivate cow peas or beans, and so avoid floods. The interviewees predict a widespread increase in flood hazard due to climate change, with their agricultural consequences shown in Figure S6 of the supplementary material. The following negative consequences of climate change and floods on agriculture were identified in order of frequency of mentions:

- Loss of crop yield (88%)
- Destruction of infrastructure and property (63%)
- Loss of livelihood (50%)
- Decrease in food security (50%)
- Displacement of animals (cattle) (38%)
- Loss of stocked/stored harvests (38%)
- Losses of equipment or inability to use equipment (38%)
- Loss of life (38%)
- Out-migration of farmers (resettlement) (25%)
- Loss of fertile topsoil (25%)
- Increase in erosion sensitivity (25%)
- Loss of farmland (13%)
- Increase in pests and diseases (13%)
- Inability to harvest crops (13%)
- Loss of economic investments (13%)
- Loss of economic trees (13%)

4.3 Exposure

Results of the exposure factors mentioned by the interviewers can be categorised into four main factors: (i) extent of farming activities (100%), (ii) proximity to Bagre Dam (63%), (iii) location up- or downstream (50%), and (iv) presence of infrastructure (50%) (see Figure S7 of supplementary material). The main exposure factor is the presence and extent of farming activities in the floodplains or close to the river or its tributaries. Given that the intensity and frequency of floods are expected to increase, the mere presence of agriculture in the floodplains increases exposure to floods. Since rainfall is often not a reliable source of water, farmers turn to irrigation or farming close to the river where there is a good amount of soil moisture and nutrients, mostly due to flood recession. Therefore, the closer a farmer is to the river, the more profitable the farming becomes because less money is needed to purchase fertiliser and irrigation equipment. Farmers prefer these benefits over flood risk.

The location of farming infrastructure and housing up- or downstream impacts flood exposure level for farmers. Upstream areas face higher flow velocity and energy during floods, with most floods originating upstream or near Burkina Faso. Respondents noted that infrastructure is often not flood-resistant, and the lack of critical information and data affects calculations during construction, which leads to damage to roads, bridges, farmhouses, and crop storage during floods. This hinders transportation, trade, and livelihoods, leading to problems for farmers. Upper East has the highest exposure due to its upstream location, proximity to the Bagre Dam, and high floodplain farmland abundance, followed

by North East, Northern, Savannah, and Upper West, in decreasing order of exposure (Fig. 3).

4.4 Vulnerability

4.4.1 Sensitivity

Results of the sensitivity elements were grouped into eight main factors according to the interviewees (Figure S8 in supplementary material) including (i) proximity to Bagre Dam (63%), (ii) soil erosion (50%), (iii) river siltation (50%), (iv) crop type (50%), (v) vegetation type and cover (38%), (vi) soil characteristics (25%), (vii) crop maturity time (25%), and (viii) poor infrastructure and buildings (13%). Operations at the Bagre Dam in Burkina Faso are an important exposure and sensitivity factor. It is the cause of annual floods in the Northern region. Respondents explained that the catchment in northern Ghana has the same rainfall pattern as Burkina Faso. When precipitation simultaneously occurs in both areas, the water holding capacity of the river system both upstream and downstream of the Bagre Dam gets saturated. Therefore, if spillage occurs, the system in Ghana cannot store this water, thereby causing a flood. This will also lead to a backwater effect in the tributaries of the system. Hence, the sensitivity will be greater closer to the Bagre Dam.

Some crop types are more flood-sensitive than others. Ground nuts, guinea corn, maize, yam, cassava, corn, and grasses are among flood-sensitive crops. Other crops, like rice, and
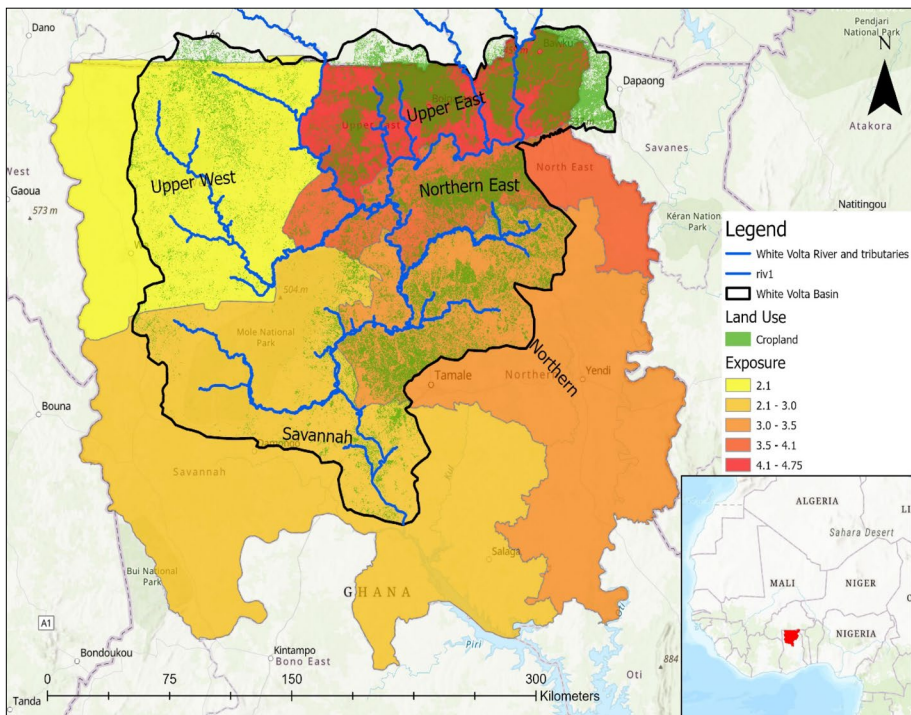
Fig. 3 Exposure to floods in the agricultural sector

economic trees like the Shea tree, the Baobab tree, and the African locust bean tree can withstand floods better. These trees are important suppliers of local foods. Flood-sensitive crops have a shallow rooting depth. So, during a flood, together with the top part of the soil, the whole plant including roots is washed away. Anthropogenic activities near the rivers, such as farming, mining, building, and erosion, cause siltation of the river downstream, which heightens the riverbed. These activities soften and loosen the soil, which is transported to the river during rains and floods. This process of siltation has become so extensive that the flood sensitivity downstream increases significantly.

Soil erosion is another main reason for the sensitivity. Anthropogenic activities and wrongful (mechanic) farming practices, as well as the use of chemicals and (illegal) deforestation, cause the soil to degrade, erode, and eventually lay bare. This means that the fertile topsoil will be easily washed away, and the vegetation that serves as natural barriers to flood will disappear, thereby increasing the sensitivity of farmlands.

Results show that the Upper East is the most sensitive region in the area (Table S1 in supplementary material). The region is high upstream, so flood water flows with high energy. This, in addition to a harder soil surface which hampers the infiltration speed, makes the region sensitive. Given that they are located upstream, the North East region is the second most sensitive followed by the Northern region. Furthermore, the main cultivated crop in North East is rice, which has a lower sensitivity than other crops and a lower exposure since it is cultivated further from the river. The respondents added that due to siltation and erosion of soils, the sensitivity remains high. The Northern region is fairly flat and easily gets waterlogged. Even though erosion is not as severe as in the Upper East, the floods and the inundations have to do with the stagnation of runoff water. The border of the Upper West with the Upper East seems to be the most sensitive in this region, according to the respondents.

Other than the water bodies in the Upper East, those in the Upper West region do not get so many rains that result in floods. The Savannah region ranked as the fourth and least sensitive region due to its proximity to the transitional zone with lots of vegetation that helps reduce floods. Also, the region has a lot of large-scale farming in addition to alternative livelihoods raising the economic standards of the people and reducing their sensitivity.

4.4.2 Adaptive capacity

The interviews resulted in a list of identified adaptation measures currently being implemented against floods; Figure S9 in the supplementary material shows the whole list including frequency of mention. The following measures were identified from most used to least used:

- Government programs/education (63%)
- The use of modified seeds/low-maturity crops (63%)
- Building of reservoirs and dams (50%)
- Available weather data and forecasts (38%)
- Livelihood diversification (38%)
- Restoring vegetation along the rivers (38%)
- Dredging of river channels (25%)
- Early warning system (25%)
- Diversification of crop type (25%)

- Irrigation systems (25%)
- Resettlement (25%)
- Indigenous practices (13%)
- Change of temporal cultivation pattern (13%)

More than half of the interviewees emphasised the importance of government programs in educating farmers and the local population on the risks of farming in the flood plains and providing actionable knowledge through workshops and seminars to increase adaptive capacity. However, some respondents found these programs and warning systems limited due to accessibility challenges; not all farmers have access to the internet, television, or even radio to access reliable weather and hydrological forecast information. Agriculture extension services that could help ameliorate the problem are also limited in delivery. Farmers who have access to this information also mistrust the sources and therefore do not use them.

Results show that the use of modified seeds to shorten the maturity period of crops is one of the ways farmers try to increase their adaptive capacity. Decreasing the crop maturity time implies harvesting 2 weeks or a month earlier before floods occur to prevent crop destruction. Furthermore, the construction of reservoirs and dams is also a feasible adaptation measure, given that they enable flood dampening and flood water storage for later use for irrigation. For example, the planned multi-purpose Pwalugu Dam is aimed to store flood water from the Bagre Dam spillage, for irrigation, hydropower generation, and flood hazard reduction.

The Northern region has the highest adaptive capacity (Table S1) due to its relatively high resources, human capital, institutional capacity, and infrastructure, particularly in Tamale. Farmers in this region have better flood adaptation knowledge and weather information access. The North East region has a similar capacity but lacks good water storage infrastructure. The Upper East region has fewer capacity measures which often do not work due to the low response time to floods. Even though they also have relatively high human capital, they have high exposure and therefore need to increase their adaptive capacity. Upper West and the Savannah regions have the lowest adaptive capacity. Figure 4 shows the vulnerability per region by combining adaptive capacity with sensitivity.

4.5 Composite flood risk

Flood risk for all regions is shown in Fig. 5. The total scores for the three components hazard, exposure, and vulnerability per district can be found in Table S2 in the supplementary material. Upper East region has the highest flood risk, followed by the Northern East region, Northern region, Savannah region, and Upper West region. Flood risk slightly increased for all regions during 2021–2040, stabilised during 2041–2060 and 2061–2080, and then gradually increased again in the last 20 years, particularly in the Upper East region. The effect of change in socio-economic stressors and societal change is thus not considered. The total flood risk increased by 19.1% from 2006 to 2100 compared to the historical period.

Results in Fig. 6 show the complete impact chain for "The risk of crop yield loss due to floods". Some of the sensitivity and exposure factors were combined if they had an impact on the same intermediate impacts and therefore not included in the impact chain. Some capacity factors were also left out not because they are irrelevant to agriculture flood risk but because they do not relate to the risk of crop yield loss.
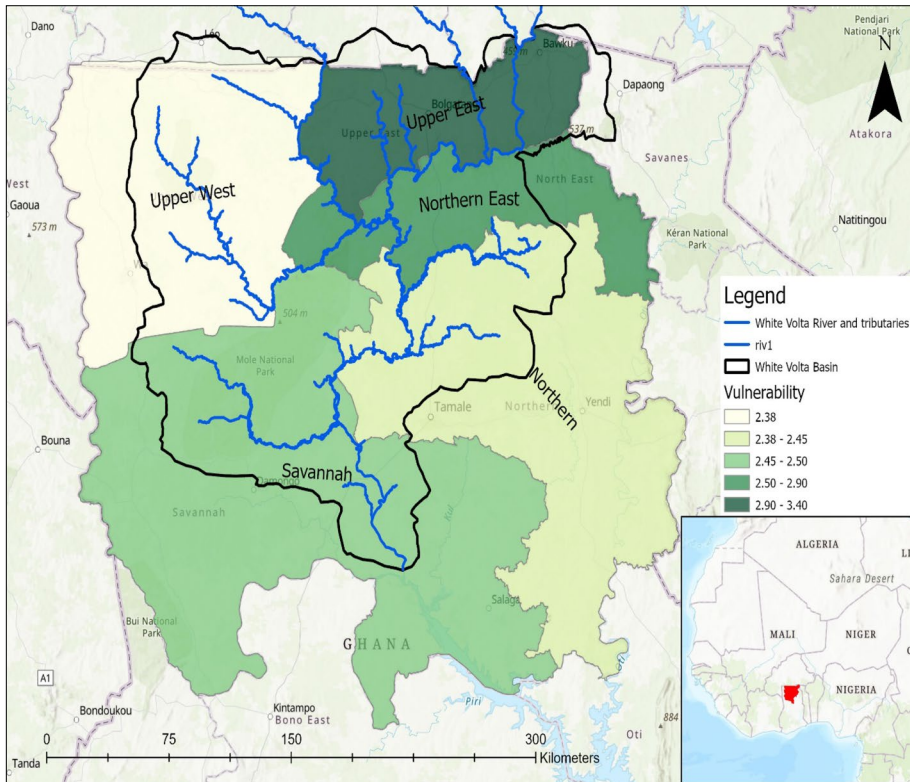
Fig. 4 Vulnerability of agriculture systems to floods per region

## 4.6 Underlying causes of flood risk

Farmers' religious and indigenous ties to their lands are among the reasons farmers stay or farm in exposed areas despite their knowledge of the destructive impacts of floods. As such, culture remains an essential consideration for developing and communicating effective climate adaptation policy.

Land tenure remains a key causative factor for flood impacts. Farmlands are owned by a few affluent individuals and are often inaccessible to many farmers. This problem of land-ownership is especially predominant in the Upper East region pushing many to farm on floodplains.

According to the respondents, farmers are limited in what they can grow because of market demands that limit production to a few crops. Farmers can therefore not simply switch to crop types with limited demand, even if new varieties are flood-resistant.

4.6.1 Future needs for social transformation

Almost all interviewees agreed (75%) to the need to increase adaptive flood infrastructure, awareness and education programs, and more enforcement of policies and laws regarding
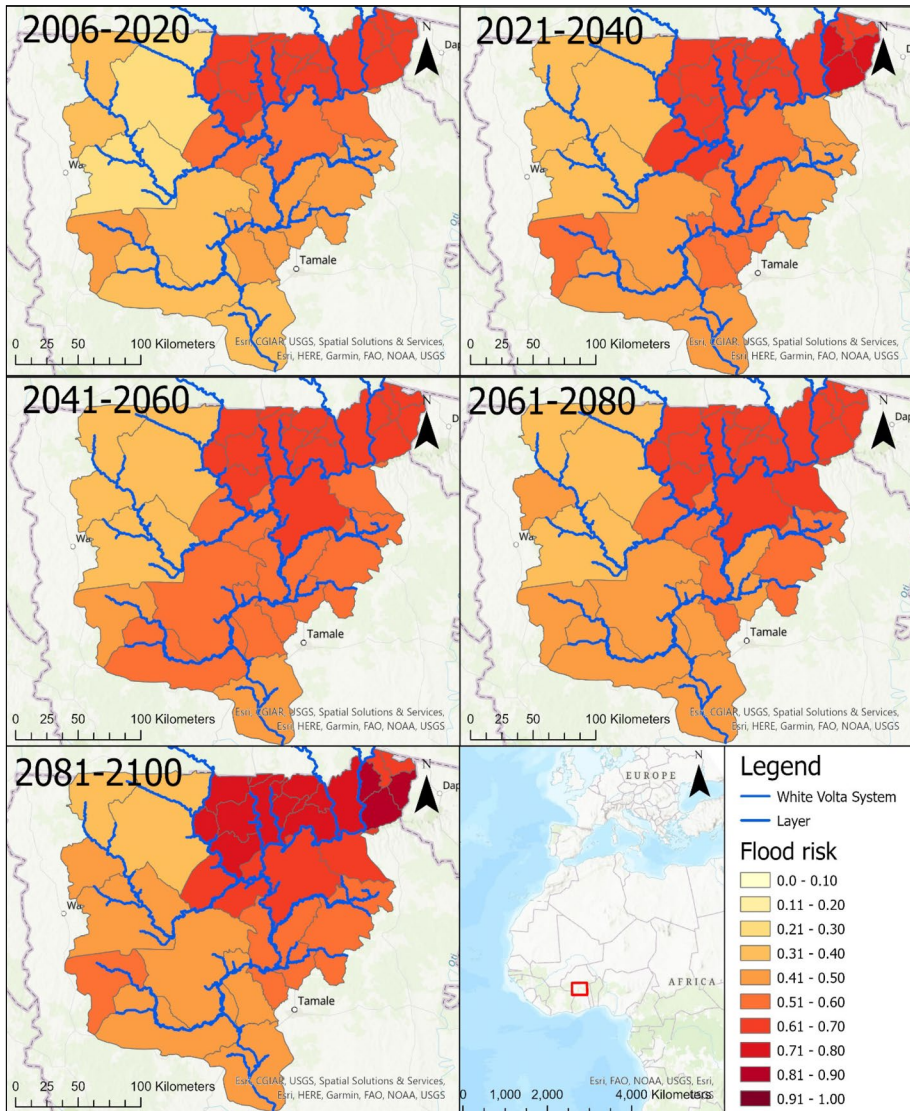
Fig. 5 Composite flood risk for agriculture for all five time periods in the White Volta Basin in Ghana

unsustainable practices and illegal farming and housing. Figure S10 of the supplementary material shows the total list of topics that should be addressed to increase capacity, including the frequency of mentions by the respondents. Besides the three above-mentioned topics, the list also includes the following:

- Capacity building on all levels (50%)
- Early warning systems/forecasting (50%)
- Alternative livelihoods (38%)
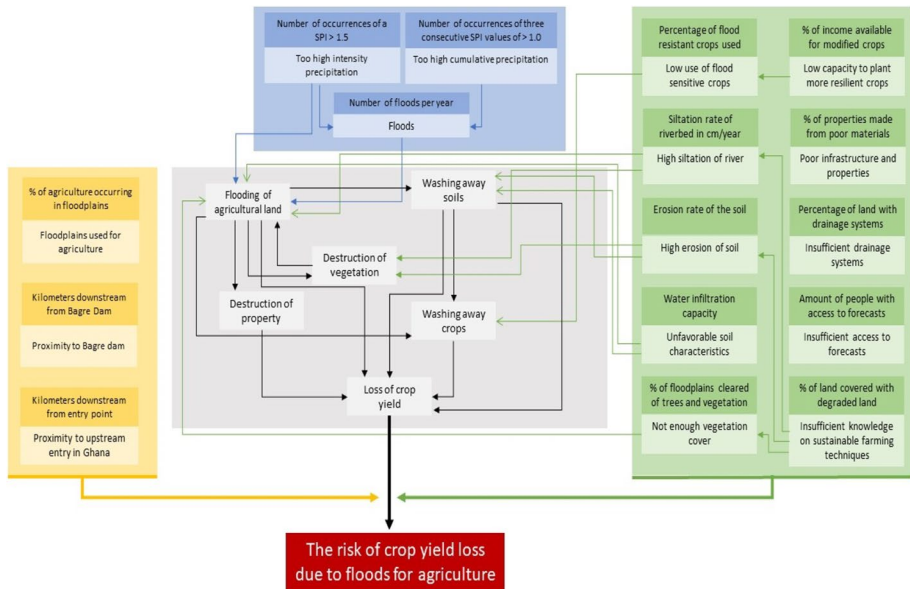
Fig. 6 Impact chain for "The risk of crop yield loss due to floods for agriculture". The blue area represents the hazard component, the green area is the vulnerability component, and the yellow area is the exposure component. In the grey area, the intermediate impacts are linked to the components of hazard and vulnerability

- Resettlement (38%)
- Rehabilitation of degraded areas (38%)
- Climate-smart crops/short variety or flood-resistant (38%)
- Implement research findings in policy (25%)
- Stakeholder involvement (bottom-up policy) (13%)
- Government buy-in (13%)

The respondents explained that several laws exist but that there is no enforcement, so degradation, erosion, and siltation still occur due to illegal and unsustainable practices. Half of the interviewees agree that, for future vulnerability to be reduced, there needs to be capacity building on several levels. These include money, knowledge, human resources, and (inter-agency) management. They explain that there should be budget allocations at the sub-national level to address infrastructure, education, and capacity building of both technical staff and farmers.

5 Discussion

This study aimed to determine the extent to which the agricultural system in the White Volta Basin in Ghana is at risk of climate change-induced floods. The research uncovers a range of findings with significant implications for flood risk management in the White Volta Basin.

Results showed an increase in flood hazards over the century, marked by intensified precipitation events and prolonged wet periods in the study area. However, there is no consensus in the literature about precipitation trends; some studies report decreases (Dickinson et al. 2017; Yaro 2013), while others note increases or stabilised patterns (Haarsma et al. 2005; He et al. 2022; Klutse et al. 2021).

The top four flood impacts identified include loss of crop yield; destruction of infrastructure and property; decrease in food security; and loss of livelihood. These results align with previous research by Musah et al. (2013), which highlighted the devastating effects of floods on farmers' livelihoods, including damage to crops, houses, infrastructure, and health facilities in Tolon and Kumbumgu Districts located in the basin. Also, several exposure factors contribute to flood risk, including farming activities in the floodplains; proximity to the Bagre Dam; location up- or downstream of the catchment; and presence of infrastructure. The proximity of communities to the White Volta or Black Volta River is a significant exposure factor, and the Bagre Dam serves as an example of transboundary climate risk, affecting local climate hazards in Ghana while extending across the country's border into Burkina Faso (Abass et al. 2022). This study underscores the complex challenge of adaptation in Ghana and emphasises the need for transboundary cooperation and negotiation in developing effective adaptation measures (Almoradie et al. 2020). The findings highlight the intricate dynamics of flood risk in the region and the imperative of considering exposure and vulnerability factors in devising comprehensive flood risk management and adaptation strategies.

The study identifies critical sensitivity factors influencing flood vulnerability, including soil erosion, river siltation, and crop type followed by vegetation type and cover. Poor land cultivation practices and inadequate farming activities have been found to exacerbate soil erosion, heightening the vulnerability of nearby communities (Almoradie et al. 2020; Ayivor & Gordon 2012; Gordon et al. 2013; Mohammed et al. 2013; Tahiru et al. 2020). In a study by Abass et al. (2022), silted rivers, illegal mining, and sand-winning activities are also seen as triggers for floods. Furthermore, the presence of vegetation is noted to significantly reduce runoff and soil erosion, serving as a vital control for overland flow (Tahiru et al. 2020). These sensitivity factors underscore the need for improved land management practices and ecological measures to reduce flood vulnerability and enhance resilience.

Results show that adaptation measures that build the adaptive capacity include government programs on education, the use of modified seeds and low-maturity crops, and the building of reservoirs and dams. Antwi-Agyei et al. (2018) highlight various adaptive and coping strategies for farmers in northern Ghana to employ; these include "extensification and intensification of agriculture, temporary migration, cultivation of drought resistant varieties, mulching, etc.". However, adaptation strategies are also limited in several ways. Existing flood risk measures tend to be more reactive than preventative, relying heavily on short-term interventions and external funding (Almoradie et al. (2020). Financial and technical challenges further hinder the maintenance of these systems. One significant finding is the weak institutional coordination in flood risk management and disaster risk reduction, leading to operational failures due to a lack of synergy among government agencies. Furthermore, the study reveals legislative gaps in the study area concerning flood risk reduction. Almoradie et al. (2020) listed gaps in legal instruments: lack of a law addressing risk reduction, inadequate flood zone and buffer zone regulation, and insufficient dumping law regulations. Respondents in the study also note similar deficiencies. Weaknesses in Ghana's risk reduction strategy extend to spatial planning policies and the performance of flood hazard and risk assessments,

as well as shortcomings in hydrological and meteorological models (Almoradie et al. 2020; Juhola et al. 2016).

The findings reveal that certain adaptive strategies have led to maladaptation, aligning with the work of Antwi-Agyei et al. (2018) and Juhola et al. (2016) who identified three types of maladaptation: rebounding vulnerability, shifting vulnerability, and eroding sustainable development. Despite farmers' confidence in current adaptive strategies among farmers, they acknowledge the need to address their limitations. To bridge these gaps, many farmers turn to indigenous knowledge, as highlighted by Attoh et al. (2021) and Guodaar et al. (2021). These farmers employ various indigenous practices at the individual and household levels, including rainwater harvesting, relocating farms to water sources, and using neem leaf extract and organic manure. Communities collectively engage in activities like congregational prayers, rainmaking rituals, and tree planting. Indigenous ecological indicators are also utilised for rainfall forecasts, as documented by Nyadzi et al. (2021a, b). These indigenous approaches offer valuable insights into enhancing resilience and should be integrated into broader adaptation strategies.

The study indicates that, under the RCP 8.5 scenario, the Upper East region exhibits the highest flood risk, followed by the North East, Northern, Savannah, and Upper West regions. Also, flood risk has increased significantly throughout the twenty-first century. He et al. (2022), utilising an HBV-model study driven by five Global Climate Models (GCMs), observe a general increase in total annual precipitation in northern Ghana during the coming century, contributing to heightened flood risk. Their findings further highlight an 86% decrease in the return period of discharge and floods under the RCP 8.5 scenario in Ghana. Moreover, a 624% surge in population exposure to flood risk in the country's major river basins, relative to the reference period of 1961 to 1990, was reported (He et al. 2022). These findings align with earlier research by Hirabayashi et al. (2013), corroborating the anticipated increase in flood risk associated with changing climate conditions.

The methodological approach used in this study combined quantitative with qualitative approaches, offering better insight into climate risk assessment and a deeper understanding of the social system under study. This methodology distinguishes itself from almost all flood risk analysis methods. In that, most used flood risk analyses are quantitative modelling and simulation, statistical analysis, and GIS techniques with little to no emphasis on qualitative research methods (Diaconu et al. (2021). However, effective adaptation and mitigation strategies necessitate a comprehensive understanding of the social context and perspectives, which the adopted impact chain method successfully achieves. The impact chain method provides a clearer understanding of the interrelationships among various components concerning flood impact. Policymakers can employ this method as an assessment tool to inform and enhance flood risk management and adaptation strategies for the agricultural sector, thereby promoting more holistic and effective flood risk reduction.

In this study, we recognised some limitations that may have affected the outcome of the study. *First*, two primary sources of uncertainty were identified in the impact chain analysis: *(i)* the uncertainty inherent in the climate models, the precipitation data, missing data, and the SPI method and calculations (Dickinson et al. 2017; Hijmans et al. 2005); and *(ii)* expert bias in the exclusion and assignment of weights to various elements within the assessment, which could substantially influence the risk assessment outcome. *Second*, using SPI as a proxy for floods might not offer a precise indication of the flood occurrence due to the complexity of the relationship between meteorological conditions (as represented by SPI) and actual flood events. Flooding is influenced by various factors beyond precipitation, including terrain, land use, and local infrastructure. While SPI provides a regional perspective on precipitation, floods are locally diverse, resulting in a weak

correlation in our initial analysis. This underscores the need for further research, involving other variables and modelling approaches to better understand and predict flood risk. Since flood events in the study area are often influenced by short-term weather patterns, such as those occurring between July, August, and September, which lead to saturated soil conditions, future studies should consider broader SPI accumulations (e.g. SPI-6 or SPI-12) and incorporate hydrological models to provide a more comprehensive assessment of flood hazards, including return intervals and probabilities. *Third*, the limited number of historical flood events identified in the extensive literature review could potentially introduce biases. This limitation arises from the fact that only unprecedented historical flood events are often recorded. However, we prioritised data quality and opted for smaller but well-documented, reliable, and detailed historical flood events. Despite this choice, it is essential to acknowledge that the dataset may not encompass the full spectrum of flood events, possibly affecting the generalisability of the findings. *Fourth*, although the selected CORDEX models have been widely used in the basin, using their data without bias correction can introduce some deficiencies in the results. The selection of the models backed with literature is not meant to imply unconditional endorsement of the models but rather to provide context for our choices. We acknowledge the variability in the performance of these models. Bias correction would indeed be a crucial step in refining these results for practical applications. *Fifth*, the total sampling size of the interview pool was just eight. Also, participants could be biased in their professional views and educational background; therefore, generalisation of the findings should be cautiously done. However, the sample covered a wide range of experts from relevant fields, and the in-depth interviews with experienced experts in relevant organisations provided invaluable insights into the local social context, which is hard to derive from literature but essential for understanding the root causes of flood risk.

6 Conclusion

Flood as a hazard will increase by 79.1% with high spatial variability of wet periods but the flood risk will increase by 19.3% by the end of the twenty-first century over the whole catchment. Further findings show that exposure is related to the presence of agriculture near main river streams, as well as the proximity to the Bagre Dam and the location in the catchment. The sensitivity of agriculture is mainly caused by soil erosion, river siltation, crop type, and vegetation cover in the floodplains. Additional causes of sensitivity are related to soil characteristics, maturity time of crops, and the state of infrastructure and properties. The adaptive capacity mostly relies on government interventions and education for farmers, the use of short-maturity seeds and some flood-resistant seeds, and the use of reservoirs and dams. Other measures currently employed include the restoration of vegetation, livelihood diversification, and the use of weather and seasonal climate forecasts for farmers. Underlying causes for the elevated exposure and vulnerability and low capacity in the region originate from poverty, low capacity from the (regional) government, and an overall lack of livelihood alternatives. The highest flood risk is found in the Upper East region, followed by North East, Northern, Savannah, and Upper West for all future periods. Finally, the impact chain methodology that combined qualitative and quantitative approaches has served as a useful tool in bringing together the worlds of social and natural sciences to generate insight into an inclusive flood risk assessment for policymakers and researchers in the agricultural sector in Ghana and beyond.

Data availability The datasets generated and/or analysed during this study are stored on the WUR repository and are not publicly available. They are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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