Natural Hazards
and Earth System
Sciences

Assessing floods and droughts in the Mékrou River basin (West Africa): a combined household survey and climatic trends analysis approach

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Abstract. The assessment of natural hazards such as floods and droughts is a complex issue that demands integrated approaches and high-quality data. Especially in African developing countries, where information is limited, the assessment of floods and droughts, though an overarching issue that influences economic and social development, is even more challenging. This paper presents an integrated approach to assessing crucial aspects of floods and droughts in the transboundary Mékrou River basin (a portion of the Niger River basin in West Africa), combining climatic trends analysis and the findings of a household survey. The multivariable trend analysis estimates, at the biophysical level, the climate variability and the occurrence of floods and droughts. These results are coupled with an analysis of household survey data that reveals the behaviour and opinions of local residents regarding the observed climate variability and occurrence of flood and drought events, household mitigation measures, and the impacts of floods and droughts. Based on survey data analysis, the paper provides a per-household cost estimation of floods and droughts that occurred over a 2-year period (2014–2015). Furthermore, two econometric models are set up to identify the factors that influence the costs of floods and droughts to impacted households.

1   Introduction

Extreme meteorological events such as droughts and floods represent an important limitation for the development of the poorest countries, cause loss of lives, damage to dwellings and vulnerable rural infrastructures, reduction of capital stock, and agricultural and industrial production losses. They also pose a general threat to food security and development, leading to shocks in labour productivity, energy security, and political instability (Dell et al., 2014; Hsiang, 2010). In developing countries, agriculture remains the main economic activity, and farming practices are mainly represented by rain-fed agriculture (Rosegrant et al., 2002). Agriculture, a sector extremely vulnerable to extreme events, is the main source of income and often the only means of self-sufficiency of the poorest portions of the rural population in the least developed countries, including sub-Saharan Africa (Gautam, 2006; Hellmuth et al., 2007). Floods and droughts, together with other natural disasters, were found to have a particularly damaging impact on the African continent, in particular with respect to fatalities, affected population, and economic damages (Cavallo, 2011). A recent study (Shiferaw et al., 2014), for instance, found that frequent drought conditions have limited the economic growth of many African countries and frustrated the benefits derived from development strategies implemented in the education and technological innovation sectors, confirming the findings of a previous study (Toya and Skidmore, 2007). Reduced precipitation was found to be responsible for about 15 to 40 % of the gap between the per capita gross domestic product of African economies and that of the rest of the developing world (Barrios et al., 2010). The negative impact on economic growth of the stresses due to ever-increasing dry con-

ditions and precipitation was also confirmed by Berlemann and Wenzzel (2015), who found drought-prone countries to be generally characterised by lower education levels, lower saving rates, and higher fertility levels. For these reasons, in the recent past, the disaster risk management community has extensively worked on the development of methodologies that aim to monitor the risk-prone areas and the overall vulnerability of the population threatened by the hydrometeorological hazards (UNISDR, 2017, 2013, 2011,2008, 2004). Progress has been made in the assessment of the occurrence of extreme events, their magnitude, and the expected climate change impacts (Alfieri et al., 2012; Hallegatte, 2012). Additional efforts were directed towards the improvement of both the assessment of risk and the estimation of the direct and indirect impacts, in particular those related to loss of human lives, economic activities, infrastructure, and natural and man-made capital (UNISDR, 2015). Technical advancement efforts also allowed for an improved assessment of current mitigation measures and policies (Bouwer et al., 2011; Bubeck and Kreibich, 2011; Green et al., 2011; Logar and van den Bergh, 2011; Markantonis et al., 2012). However, the benefits derived from the progress made in this discipline were mainly concentrated in the most developed and technically advanced countries, where information is more readily available and mitigation strategies are more likely to be effectively implemented (UNISDR, 2015). In the case of African countries, the assessment of the physical impacts of hazard events followed the general level of technical development. As in the most advanced countries, in fact, the occurrence of floods and droughts was assessed by applying remote-sensing-based techniques, analysing precipitation and temperature records and their spatiotemporal distribution, as for instance in a case study in Kenya carried out by Ngigi et al. (2005).

Although several quantitative and qualitative approaches have been developed in assessing costs of natural hazards, information about losses caused by past extreme events is still too limited to facilitate a detailed cost estimation and impact assessment analysis for many African countries. As described in Markantonis et al. (2012, 2013), the methodologies used in the literature are various: hedonic pricing, travel cost, cost of illness approach, replacement cost, contingent valuation, choice modelling, and life satisfaction analysis (Welsch and Kühling, 2009; Luechinger and Raschky, 2009; Welsch, 2006). In this study, however, it was decided to estimate the cost of natural disasters in the case study area based on the direct testimony of the affected population. Several studies used household surveys to acquire qualitative and quantitative information from the local population in order to estimate the damages of past hydrometeorological events (as, for instance, in Fitchett et al., 2016; Ologunorisa and Adeyemo, 2005). Depending on the key economic sectors of the case study area, various examples of cost and impact assessment could be listed. Among the most representative were studies analysing the following sectors: health (Schmitt

et al., 2016), agriculture and food security (Ngigi et al., 2005; Shiferaw et al., 2014; Shisanya and Mafongoya, 2016), and tourism (Fitchett et al., 2016). An analysis of the hazard components and the various impact assessments conducted in the recent past allowed for the evaluation of risk mitigation measures and adaptation strategies. For instance, Shisanya and Mafongoya (2016) analysed the effectiveness of shifts in agricultural practices; Brower et al. (2009) focused on the evaluation of the installation of risk mitigation infrastructures; Oyekale (2015) analysed the implementation of more advanced forecasting and early warning systems; Halsnæs and Trærup (2009) focused on the implementation of specific integrated policies and practices for floods and droughts. In some of these studies, cost–benefit and willingness-to-pay analyses were used to add quantitative evidence to the qualitative descriptions.

The objective of this paper is to assess the occurrence of flood and drought events, estimate damage costs at the household level, and describe the current mitigation behaviours adopted by the population of the Mékrou River basin, a small catchment area in West Africa. It combines a quantitative approach for detecting hydrometeorological hazard-prone areas (through the analysis of gridded climate datasets) with a qualitative and quantitative analysis of a household survey. This approach allows for the comparison of physical analyses of extreme events with human perceptions of the flood and drought phenomena in the Mékrou River basin. The household survey provides sufficient information to estimate the impacts of natural hazards in terms of economic cost and to present the most widely adopted mitigation behaviours.

Mékrou is a sub-basin of the Niger River, covering an area of $10\,635\,\mathrm{km}^2$, about 3 % of the total Niger basin surface, across three countries Benin (80 % of the basin territory), Burkina Faso (10 %), and Niger (10 %). Mean annual precipitation ranges from a maximum of about 1300 mm in the southern region and 500 mm in the north. The wet season occurs between June and September, with average cumulated rainfall of 700 mm. Temperatures are also highly variable in space and time. The warmest and coldest months are April and September, respectively. Mean annual temperatures vary between 26 and 30 °C, reaching a maximum of 35–40 °C and minimum of 15–19 °C. The Mékrou catchment is located in a temperate transitional area characterised by a wet season that peaks in August and a long dry season that spans the period December–April (Masih et al., 2014). During the wet season, the whole Niger River basin is subject to regular floods. Extensive research has been conducted on its complex hydrology, which is characterised by a large system of lakes and wetlands known as the Inland Delta (Bader et al., 2016; Tarpanelli et al., 2017), while less attention has been given to the Mékrou sub-basin. Flood and drought events are extremely frequent (Froidurot and Diedhou, 2017), and the impacts of climate change on their frequency and magnitude is unclear (Gautam, 2006). The Mékrou River basin is characterised by lack of or poor infrastructural development and

very low socioeconomic conditions. Agriculture is the key economic sector, with the arable land used for food production, cattle farming, and the production of cotton. Therefore, climate variability is the main threat to the food and economic security of the area.

This paper is structured as follows: Sect. 2 presents the methodological framework regarding the development and application of the household survey (Sect. 2.1) and the analysis of the biophysical variables (Sect. 2.2). The findings of this integrated approach are given in Sect. 3. This section analytically presents the findings regarding precipitation patterns, temperature, and river discharge in the Mékrou River basin. Moreover, it includes the main findings of the household survey concerning the observed occurrence of floods, droughts and climate variability, household mitigation measures, the impacts of floods and droughts, and an econometric estimation of the costs of floods and droughts. Section 4 summarises the main findings of this approach, discusses its potential and limitations, and presents the main conclusions.

2 Methodology

2.1 Household survey implementation and analysis

A household survey to evaluate several water-related dynamics, including extreme natural hazards, was designed in 2015 and conducted in early 2016 (February to April). Specific villages and towns were selected to include a geographically representative sample of the river basin that belongs to the three countries (Benin, Burkina Faso, and Niger). The selection process was designed to keep a balance between urban and rural settlements. The number of households proportionally represents the total population of the respective villages or towns selected, and the number of households per country represents the country's population within the basin. Since there were no available lists of households that include their socioeconomic conditions we have selected them randomly based on their location in the village/town, keeping a distance of five households between those interviewed. Table 1 presents the detailed sample and population of the selected villages. The survey was carried out by experts of the Joint Research Centre of the European Commission in cooperation with local universities from Benin, Niger, and Burkina Faso. Interviews were conducted in person by a team of students supervised by a professor for each country. Before starting the survey, the students received training in which the questionnaire was thoroughly explained and discussed. Since the area is francophone, all the material used was written in French. The fact that the survey was conducted by students of local universities facilitated communication with the local population, overcoming possible language and cultural barriers. Prior to the conduction of the survey the survey country administrators visited each selected village and informed the local authorities. This process secured the ac-

ceptance of the survey on the ground, resulting in a 100 % response rate. The information included in the household survey aimed to retrieve opinions and observations based on personal judgement. A large section of the survey focused on identifying and assessing the impacts and costs of flood and drought events, climate variability, and household mitigation measures. Regarding the occurrence of floods and droughts in the study area, two time periods were selected: 10 years (2006–2015) and 2 years (2014–2015). The logic behind this selection was to identify the most recent events (2 years), for which the local households still had a fresh memory of the impacts suffered. The second time period (10 years) offers a longer assessment of climate variability and the occurrence of floods and droughts, which could potentially still be evaluated according to personal judgement. The whole questionnaire is included in Appendix A.

The survey process resulted in the collection of 660 randomly surveyed questionnaires retrieved from the areas of the three countries (Benin, Burkina Faso, and Niger) that are located in the Mékrou catchment (Fig. 1). Specifically, 332 questionnaires were collected in 16 villages from the municipalities (called "communes" in French) of Banikoara, Kouande, and Kerou in Benin; 148 questionnaires were collected in 6 villages from the communes of Diagaga and Tansarga in Burkina Faso; and 180 questionnaires were collected in 8 villages from the communes of Falmey and Tamou in Niger. The total number of surveyed households offers greater than 95 % significance in the statistical findings (a minimum of 400 questionnaires are required for 95 % significance rate). In Table 2 we present basic information on the socioeconomic characteristics of the surveyed population.

Following the data cleaning and validation of the survey, the information collected was statistically analysed, including all the parameters investigated in the questionnaire. The survey responses were evaluated using descriptive statistics that aggregate data both at river basin and at country level. The findings were analysed at the river basin scale, illustrating the differences between the three countries.

Apart from the statistical analysis, an econometric estimation was applied to identify the specific parameters that are highly correlated to the costs of droughts and floods that were incurred in the last 2 years of the study (2014–2015). Hence, besides the cost estimation based on the sample mean, two econometric models were set up to investigate the determinants of flood and drought costs following a cause–effect logic. Performing a thorough multivariate regression cost analysis of floods and droughts as stated in the survey and other covariates (such as socioeconomic characteristics of the population, impacts, and mitigation measures) led to the construction of models that could be used to explain the costs of extreme hydrometeorological events. Several types of regression models were tested, both linear and logarithmic. Linear multivariate regression models were finally chosen since they fit the selected variables with a higher statistical performance level. Moreover, in order to ensure the

Table 1. Sample and population of the survey area.

Population of the Mékrou area of interest						
Benin	Burkina Faso	Niger	Total area			
294 921	79 632	173 115	547 668			

Surveyed sample (households)						
Benin	Burkina Faso	Niger	Total area			
332	148	180	660			

Sample (number of households) by selected communes						
Benin			Burkina Faso		Niger	
Banikorara	Kérou	Kouandé	Diapaga	Tansagra	Tamou	Birni Ngaoure
160	80	92	95	53	100	80

Population and sample (number of households) by selected village/town

Banikoara					
	Sampéto	Gbéniki (Kérémou)	Wangouwirou	Banikoara (town)	Total
Population	1522	786	3799	28 402	32 987
Sample	29	20	52	52	153

Kouande					
	Béket Bouramè	Mékrou-Gourou	Goufanrou	Kouandé (town)	Total
Population	1876	2635	1835	20 723	27 069
Sample	20	27	20	25	92

Kérou					
	Koussou Ouinra	Yakrigourou	Bipotoké	Kérou (town)	Total
Population	2842	2766	2871	34 246	42 725
Sample	16	19	16	36	87

Diapaga				
	Mangou	Tyaga	Diapaga (town)	Total
Population	1600	1136	16 000	18 736
Sample	28	20	40	88

Tansagra				
	Kotchari	Lada	Tansarga (town)	Total
Population	1024	720	14 000	15 744
Sample	20	16	24	60

Birni Ngaoure					
	Boumba	Fono Birgui	Kotaki	Flamey Djema (town)	Total
Population	1414	560	2447	4467	8888
Sample	12	8	20	40	80

Tamou					
	Tankoune	Diney Bangou	Foulan Walagorou	Tamou (town)	Total
Population	827	724	261	1827	3639
Sample	28	28	4	40	100

Table 2. Socioeconomic characteristics of the surveyed sample.

Age (sample respondents)							
Benin		Burkina Faso		Niger		Total Area	
Mean	SD	Mean	SD	Mean	SD	Mean	SD
41.2	14.9	44.2	16.2	49.5	15.3	44.2	15.7

Age distribution (total area population based on survey aggregation)				
	Benin	Burkina Faso	Niger	Total area
0–5	17.10 %	23.50 %	20.20 %	19.50 %
5–18	32.90 %	34.40 %	31.30 %	32.70 %
18+	49.90 %	42.10 %	48.60 %	47.90 %

Gender (sample respondents)								
	Benin		Burkina Faso		Niger		Total area	
	Count	%	Count	%	Count	%	Count	%
Male	226	68.1 %	95	64.2 %	129	71.7 %	450	68.2 %
Female	106	31.9 %	53	35.8 %	51	28.3 %	210	31.8 %

Education (sample respondents)					
	No schooling	No formal school	Primary school	Secondary education	Professional	University
Count	389	87	81	78	8	17
%	58.90 %	13.20 %	12.30 %	11.80 %	1.20 %	2.60 %

Profession (sample respondents)					
	Unemployed	Self-employed	Public employee	Farmer farmer	Livestock	Other
%	7.70 %	18.90 %	2.30 %	50.10 %	15.90 %	5.10 %

Household income (FCFA per month) EUR 1 =FCFA 656 (sample respondents)					
	0–25 000	25 001–50 000	50 001–75 000	75 001–100 000	More than 100 001	Unknown
Count	200	100	77	37	414	121
%	30.50 %	15.20 %	11.70 %	5.60 %	18.60 %	18.40 %

coherence and readability of the models, only independent variables whose p value was less than 0.05 were selected. One independent variable with a p value greater than 0.05 was included due to its importance in the context of the analysis, but its value (0.068) is still below the least acceptable p value (0.1). R-square and F-test values were estimated, and correlation among the independent variables was tested in order to avoid bias in the model due to collinearity.

2.2 Analysis of biophysical variables: precipitation, temperature, and river discharge

Precipitation and temperature patterns and changes are the main drivers of local populations' perception of water availability, especially in an area where the main economic activity is based on rain-fed agricultural production. In order to ensure an efficient interpretation of household survey's results, quantitative estimates of trends in climate-related variables are needed to understand the underlying direct (rainfall and discharge) and indirect (heat waves) factors that have an impact on the respondents answers. As analysis of rainfall events above and below the long-term average distribution in conjunction with inter- and intra-annual analyses are useful for depicting anomaly patterns and trends. They help better understand, for example, the main drivers of meteorological droughts. This is particularly relevant in order to compare local populations' perception of climate variables with quantitative estimates. Events above and below the long-term rainfall average distribution were studied in conjunction with intra-annual precipitation analysis. To complement this, we analysed river discharge regimes, as precipitation anomalies could be translated into hydrological droughts, thus generating a water resource imbalance, reduced groundwater levels, reservoir depletion, etc. (Liu et al., 2016). Secondly, considering the increasing number of heat waves that occurred during the past decade in Africa (Ceccherini et al., 2017), we
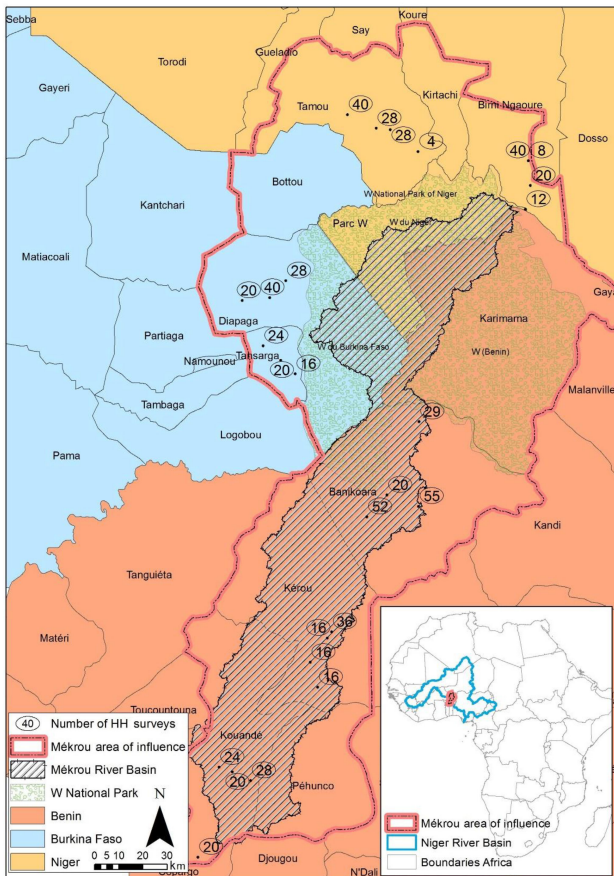
Figure 1. The Mékrou River basin and the household survey area (including number of questionnaires per village/town).

studied their magnitude and spatiotemporal evolution in the Mékrou area of influence to explain possible misperceptions that could arise in the surveys. The objective was to compare both precipitation and temperature stress with the survey results, offering empirical evidence of their concurrence or explaining the underlying causes of possible contrasting results.

2.2.1 Precipitation pattern analysis

Descriptive statistics of annual and seasonal rainfall were analysed jointly with the results of a seasonal Kendall (SK) test for monotonic trend applied to precipitation data derived from the Climate Hazards Group Infrared Precipitation with Station data v. 2.0 (hereafter CHIRPS). This database has a spatial resolution of 0.05°, corresponding to approximately 5 km (at the Equator), and covers all longitudes in the latitude range 50° S–50° N, spanning a time horizon of 1981 to the present day (Funk et al., 2014). The SK test used is based on Hirsch and Slack (1984) and it was applied over two different time ranges: the entire time series (about 35 years) and the 10-year period considered in the household

survey (2006–2015). The test is a modified version of the previous SK test proposed by Hirsch et al. (1982) and attempts to reduce the serial dependence of variables (given that seasonal precipitation data are serially correlated). Both are based on the non-parametric Mann–Kendall test (Mann, 1945; Kendall, 1975; Warren and Gilbert, 1987). The magnitude of trends are calculated using Sen's slope estimator and Kendall's tau as the rank correlation coefficient.

In addition, in order to identify precipitation anomalies, we calculated the Standardized Precipitation Index (hereafter SPI) proposed by McKee et al. (1993, 1995). The SPI measures the deviation of precipitation in a specific location from its long-term mean and is a widely used indicator for drought monitoring. This index could be applied over different timescales, each providing information about the impact of a given precipitation anomaly on the availability of water resources (WMO, 2012). In this study, the 3-month and 6-month SPIs (hereafter SPI-3 and SPI-6) were calculated, associated, respectively, with meteorological and agricultural droughts. A shorter SPI timescale is considered to be a good indicator of variations in soil moisture, while longer scales (up to 24 months) could be associated with groundwater or reservoir variations (WMO, 2012). For the purpose of this paper, as the Mékrou communities' economy is mainly based on rain-fed agriculture, we focused on the precipitation anomalies during the wet season, presenting the SPI-3 for the period June–August (JJA) and the SPI-6 for the period April to September (AMJJAS). The results are given in units of standard deviation (SD), indicating how far a given precipitation event is below (drier events are associated with a negative SD) or above (wetter event, positive SD) the long-term normal distribution of the precipitation observations in a given location. SPI values of around zero indicate a precipitation event in line with the long-term precipitation of the specific period, while negative (positive) values indicate precipitation levels below (above) historical values. SPI values could then be interpreted following a classification scheme where standard deviations are categorised into different classes, each associated with different levels of wet or dry anomalies. In this case we have divided the values following the seven categories proposed by Agnew (2000), where previous thresholds defined by McKee et al. (1993) were replaced by alternative classes (Table 3). Finally, in order to get a general overview of the anomalies in the different administrative units, we calculated the area percentage affected by each class over the entire time series.

2.2.2 Heat wave analysis

Russo et al. (2015) defined the daily Heat Wave Magnitude Index (HWMI) as the maximum magnitude of the heat waves in a year, where a heat wave is defined as a period equal to or greater than 3 consecutive days with maximum temperature above a daily threshold calculated for a 30-year reference period. The index is based on daily maximum temperatures,

Nat. Hazards Earth Syst. Sci., 18, 1279–1296, 2018

www.nat-hazards-earth-syst-sci.net/18/1279/2018/

Table 3. Standardized Precipitation Index (SPI) categorisation and associated probability of occurrence (Agnew 2000).

SPI	Probability of occurrence	Class
> 1.65	0.05	Extremely wet
1.28/1.64	0.1	Severely wet
0.84/1.27	0.2	Moderately wet
−0.84/0.84	0.5	Normal
−1.28/−0.83	0.2	Moderate drought
−1.65/−1.27	0.1	Severe drought
< −1.65	0.05	Extreme drought

taking the intensity and duration of the event into account. In our case, the source used to retrieve the maximum daily temperatures is the ERA-Interim reanalysis dataset (Berrisford et al., 2011; Dee et al., 2011) available from 1979 onwards, with an approximate spatial resolution of 80 km at the Equator. The index was applied to study these events for the past 35 years across the study area.

2.2.3 Discharge in the Mékrou River

In order to have a quantitative estimation of water availability within the Mékrou River basin, the hydrological model SWAT (Neitsch et al., 2011) was set up and calibrated to assess annual and monthly river discharge. The SWAT model integrates all relevant ecohydrological processes, including water flow, surface runoff, percolation, lateral flow, groundwater flow, evapotranspiration, transmission losses, nutrient transport and turnover, vegetation growth, land use, and water management. SWAT sub-basins were delineated using the ArcSWAT interface with a digital elevation model of 90 m spatial resolution, resulting in 32 sub-basins for the whole area.

The historical discharge data recorded at the Barou gauge station (outlet of the river basin) and at the Kompoungou gauge station (a draining area that accounts for about 56 % of the river basin) were used for model calibration. Lack of data availability represents a huge limitation for the hydrological analysis of the basin. In addition, these discharge observations are incomplete, as they are only available for a limited number of years (1990–2000 for Barou and 2004–2013 for Kompoungou). We used the SWAT-CUP program and manual setup to calibrate the outflow of the two monitoring stations and obtained satisfactory efficiency statistics (Moriasi et al., 2007) at monthly scales. In Barou, the NSE (Nash–Sutcliffe model efficiency coefficient; Nash and Sutcliffe, 1970) is 0.87 and linear regression R^2 is 0.88, and in Kompoungou the NSE is 0.77 and R^2 is 0.71. We used the SWAT-modelled discharges to consider an extended time period, required in particular to take into account climate variability and to cover areas of the basin where observations are not available.

3 Results

3.1 Biophysical variables: precipitation, temperature, and river discharge

3.1.1 Precipitation patterns

Mean annual precipitation in the study area varies from 500 mm in the northern administrative units (Bottou, Tamou, Kirtachi, and Falmey), to a maximum of about 1000–1300 mm upstream in the southern portion of the basin (Kouandé, Kérou, and Banikoara; Supplement Fig. S1). Generally, rainfall is highly variable in time and space and follows a cyclical trend of wet and dry periods. The mean monthly precipitation for the wettest month (August) in the southern and northern regions varies between 200 and 300 mm, respectively, with the driest months (November–February) being close to zero.

Comparing the precipitation patterns of a short (2007–2016) and a long period (1981–2006), it was possible to identify a slight decrease in rainfall during August and September, while a moderate increase was detected during June and July (Fig. 2). However, long- and short-term seasonal Kendall analyses, performed at a significance level $\alpha = 5\%$, were not able to identify any significant trend (Fig. 2). Some spatial differences were identified analysing the last 10 years of the study: in that regard, negative slopes were detected in the southern regions of Benin.

3.1.2 Precipitation stress analysis

The results of the SPI-3 and SPI-6 analyses highlighted a period of moderate to extreme droughts during the earlier part of the 1980s; this could also be seen in mean monthly precipitation values, where the overall rainfall from 1981 to 1985 is noticeably less than the long-term average (Fig. 3). After this period, the positive and negative anomalies were found to be more erratic, presenting alternate series of positive and negative events, such as some severe wet anomalies in the southern regions in 2003 and drought events in northern regions in 1997. Regarding the last 10 years of the study period, only a few drought anomalies affected at least 40 % of the administrative areas. The northern portion of the basin in Niger (communes of Tamou and Kirtachi) was affected by a moderate to severe drought event during 2011, while in 2014 a similar event hit the southern portion of the basin in Benin (Banikoara, Kérou, Pehúnco, and Kouandé). In contrast, severe to extremely wet anomalies were predominantly recorded during the years 2003, 2005, and 2007 in the entire Mékrou area of influence. Summarising the results derived from the analysis of the SPI, we found that the decade considered in the household survey was mainly characterised by precipitation in line with the long-term average. The anomalies were not particularly intense and most frequently related to wet conditions when considering the mete-
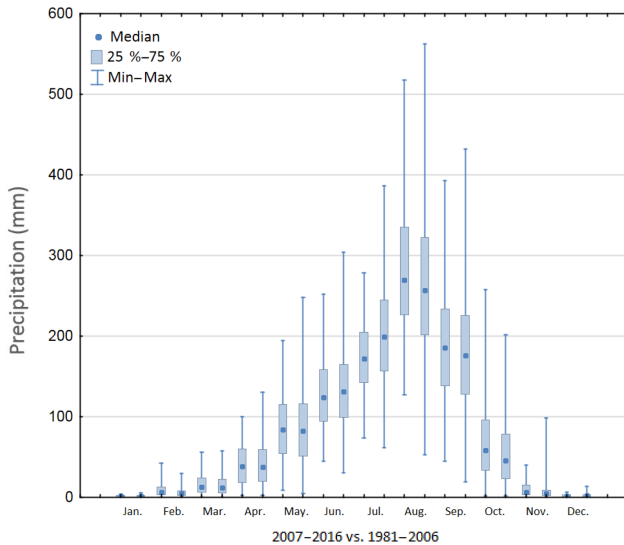
Figure 2. Box–whisker plot comparison (top) of monthly precipitation for the first 25 years of the time series versus the last 10 years (2007–2016 vs. 1981–2006). On the bottom, the results of the seasonal Mann–Kendall (MK) test for detecting significant increasing or decreasing trends (Kendall score) in the precipitation patterns for each of the areas taken into consideration in this study. The MK test was conducted using the observed precipitation records of the most recent time period (2007–2016) and the full time series available (1981–2016). The test performed did not highlight statistically significant (significance threshold p value < 0.010) increasing or decreasing trends in the analysis of the two precipitation time series.

orological precipitation stress indicator (SPI-3: 18 wet versus 15 dry anomalies), while a predominance of dry conditions was recorded when considering the agricultural precipitation stress (SPI-6: 17 dry versus 14 wet anomalies) (Figs. S2 and S3).

3.1.3 Heat waves

The spatiotemporal evolution of the HWMI between 1981 and 2015 is represented in Fig. 4. Despite some isolated events during 1987–1988 and some extremes in 1998, the analysis highlighted a constantly increasing trend in the heat wave magnitude, starting in 2004. The spatial pattern, however, is not clear, as the whole Mékrou area of influence was affected. In 2005, the HWMI was found to be higher in the central and northern parts of the basin, while the highest values in 2006 were recorded in the southern part and in 2010 in the northern part (Figs. S4 and S5).

In the period under consideration, mean annual temperature ranged between about 30 °C in the north to 26.5 °C in the south. April was the warmest month, with a maximum temperature of 40 °C in the north and 35 °C in the south. Minimum temperature in the coldest month (September) ranged between 19 °C in the north and 15 °C in the south, presenting

the semi-arid region the highest range of variation of about 25 °C.

3.1.4 River water flow trends

The annual river discharge resulting from model simulation for the period 1995–2012 is presented in Fig. 5. The first 5 years of the simulation period (1990–1994) were discarded to consider an adequate model spin-up period.

Modelled discharge in the period under consideration averaged around 24 m^3 s^{-1}, corresponding to an average annual water flow of about 760 Mm^3 (ranging from 190 to 1400 Mm^3 in 1997 and 2008, respectively). The spatial distribution of the water resources follows the topography of the basin, making the headwaters (where annual discharge remains below 100 Mm^3) particularly subject to inter- and intra-annual variability (Fig. S7). High annual variability of the river discharge is an important issue for the sustainable water use in the basin, especially considering that agriculture is the main economic activity and the lack of water storage infrastructures in the basin. Intra-annual discharge variability in the Mékrou River basin follows the seasonal precipitation patterns: most abundant flows are reached after the rainy season (July–November), with the peak flow being reached in the period August–September–October (Fig. S6).

The analysis of the simulated river flows highlighted the large interannual variability of the discharge. In about 8 of the 18 years under consideration, the average discharge was estimated to be below the long-term average by more than 20 %, while in four instances the simulated discharge was estimated to exceed the average by more than 20 % (Fig. 5). Although the analysis of the river discharge saw daily values with unusually high river discharge with respect to the average, we were not able to estimate the possible number of flood events in the domain of the study due to lack of data about flood propagation during historical events and detailed topography.

3.1.5 Analysis of the population perception on the occurrence of extreme events and climate variability

The household representatives gave their personal opinions on the occurrence of specific extreme events in the Mékrou River basin during the last 10 years of the study period (2006–2015) (Table 4). The selection of this 10-year framework allows for a relatively mid-term assessment of past climatic events. Regarding the occurrence of droughts, 86.8 % of the households declared an increasing trend in the period under consideration. This percentage is lower in Niger, but still quite high (71.5 %). In addition, the vast majority of the local population (88.5 %) estimated that the levels of rainfall decreased during the last 10 years of the study period. This result is particularly evident in Benin and Burkina Faso (93.7 and 95.3 %, respectively). Not only did the rainfall de-
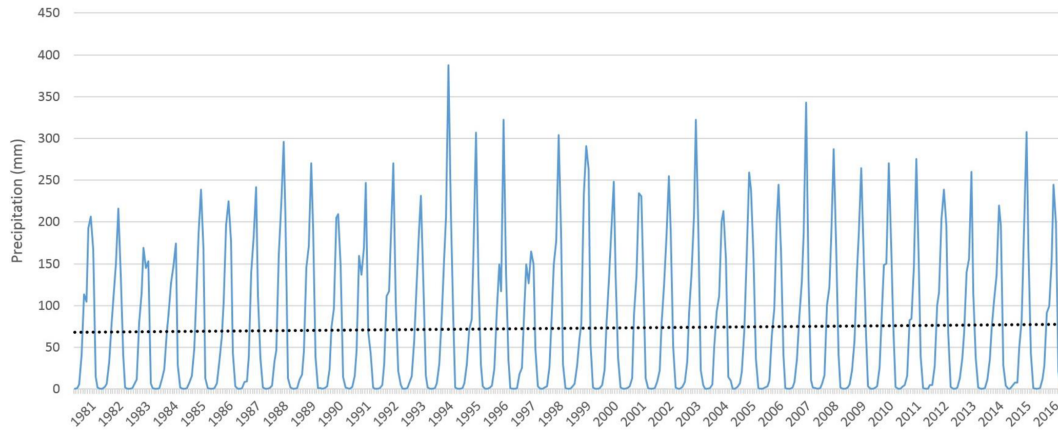
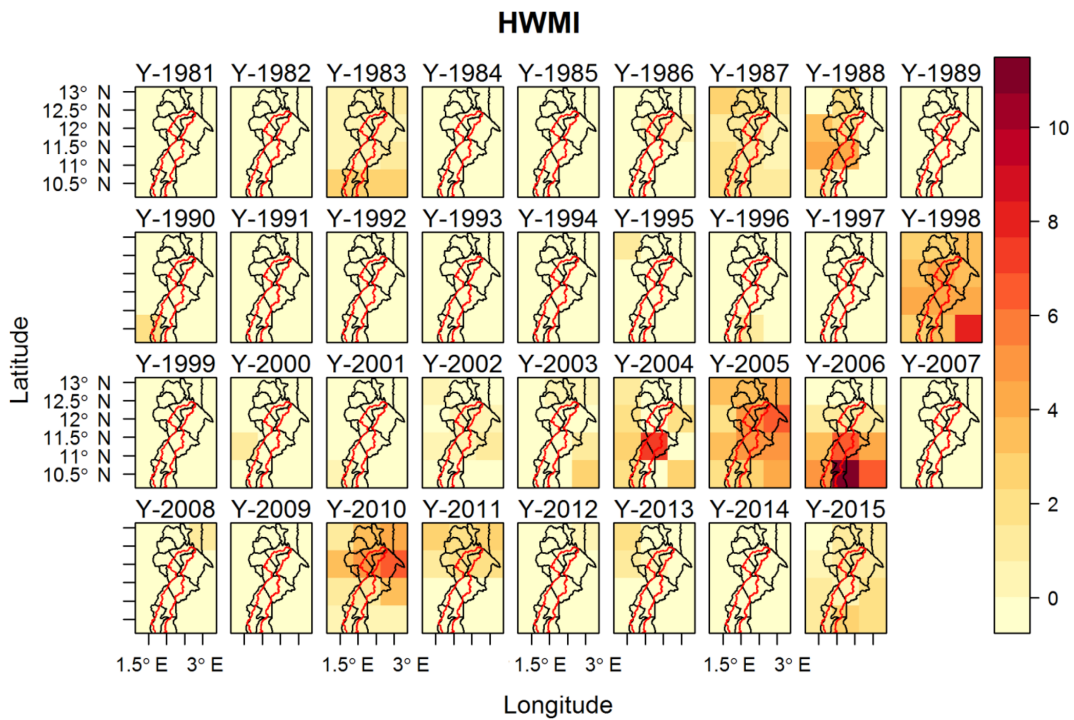**Figure 3.** Temporal monthly precipitation profile for the Mékrou area of interest.

Figure 4. HWMI computed for 1981 to 2015 for the Mékrou River area.

crease but, according to the local population (92.7 %), the seasonal distribution also changed. In fact, the majority of the respondents (83 %) stated that the rainy season started with a delayed onset during the last 10 years of the study period, whereas almost all respondents (91.8 %) declared an earlier end to the season. Regarding heat waves, 76 % of the interviewed population (62 % in Benin) stated that periods of intense heat waves became longer during the last 10 years of the study period. Regarding the number of events experienced, an increasing number of drought events were recorded, with a general frequency of 0 to 6 events. On average, the local population experienced in average 3.93 drought

events when considering the whole Mékrou River basin (Table 3). The number is higher in Burkina Faso (4.8 events) and slightly lower in Niger (3.4 events).

Concerning flood events, opinions are less homogeneous over the whole Mékrou area. The majority (62 %) of the respondents stated that flood frequency did not increase over the last 10 years of the study period. This trend is quite heterogeneous among the three countries: 84.9 % of the households in Benin agreed with the majority, while the responses are discordant in Burkina Faso, and 72.2 % of the respondents in Niger found an increasing flood frequency in the period under consideration. When asked about the number

Table 4. Observed climatic changes during the last 10 years of the study period: 2006–2015.

	Benin		Burkina Faso		Niger		Mékrou basin	
	Count	%	Count	%	Count	%	Count	%
Change of the rainfall quantity								
No change	8	2.4 %			4	2.2 %	12	1.8 %
Less rain	311	93.7 %	141	95.3 %	132	73.3 %	584	88.5 %
More rain	13	3.9 %	7	4.7 %	44	24.4 %	64	9.7 %
Total responses	332		148		180		660	
Distribution of the rainfall in the year								
No change	21	6.3 %			4	2.2 %	25	3.8 %
Better distribution	16	4.8 %	2	1.4 %	5	2.8 %	23	3.5 %
Worse distribution	295	88.9 %	146	98.6 %	171	95.0 %	612	92.7 %
Total responses	332		148		180		660	
More frequent droughts								
Yes	297	89.5 %	147	99.3 %	128	71.5 %	572	86.8 %
No	35	10.5 %	1	0.7 %	51	28.5 %	87	13.2 %
Total responses	332		148		179		659	
More frequent floods								
Yes	50	15.1 %	76	51.4 %	130	72.2 %	256	38.8 %
No	282	84.9 %	72	48.6 %	50	27.8 %	404	61.2 %
Total responses	332		148		180		660	
Delay in the start of the rainy season								
Yes	248	74.7 %	139	93.9 %	161	89.4 %	548	83.0 %
No	84	25.3 %	9	6.1 %	19	10.6 %	112	17.0 %
Total responses	332		148		180		660	
Rainy season finishes earlier								
Yes	293	88.3 %	146	98.6 %	163	92.6 %	602	91.8 %
No	39	11.7 %	2	1.4 %	13	7.4 %	54	8.2 %
Total responses	332		148		176		656	
Periods of extreme heat								
No change	34	10.2 %	10	6.8 %	15	8.5 %	59	9.0 %
Shorter	75	22.6 %	7	4.7 %	17	9.7 %	99	15.1 %
Longer	223	67.2 %	131	88.5 %	144	81.8 %	498	75.9 %
Total responses	332		148		176		656	

of flood events experienced, almost one-third of the families stated that no flood events had occurred. The remaining replies are mostly distributed among one (23.3 %), two (17.4 %), and three (13.1 %) events. As for the change in the frequency of the events, this varied across the three countries. In Benin, 60.7 % of the population did not experience any flood during the last 10 years of the study period. Large numbers of flood events were recorded primarily in Niger, followed by Burkina Faso (Table 5). In Benin, an average of only 0.7 flood events was declared during the last 10 years of the study period, while the average was 1.8 in Burkina Faso and 3.5 in Niger. The combination of these results sug-

gests that the Niger portion of the Mékrou River basin was the most prone to flood events in the period under consideration. Regarding both flood and drought events, the perceptions are heterogeneous across the three countries in the basin, with no difference based on different socioeconomic characteristics. This could be explained by the homogeneity of the socioeconomic characteristics within the basin across three countries.
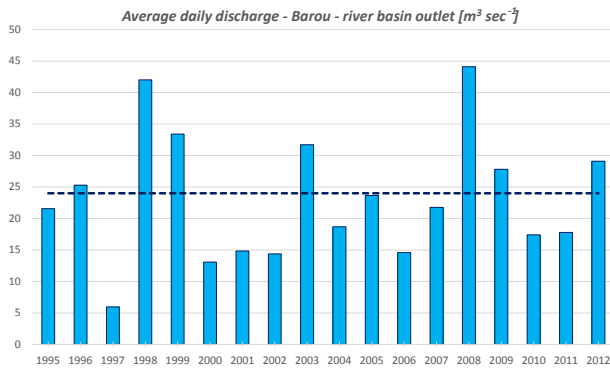
Average daily discharge - Barou - river basin outlet [m³ sec⁻¹]

Figure 5. Daily average discharge of the Mékrou River at the Barou station, as modelled using SWAT for the period 1995–2012. The dashed line indicates the average of the total period under consideration.

Table 5. Statistical analysis of reported number of floods and droughts during the last 10 years.

	Mékrou basin	Benin	Burkina Faso	Niger
Floods				
Mean	1.69	0.73	1.78	3.46
SD	2.07	1.16	1.43	2.64
Droughts				
Mean	3.93	3.83	4.80	3.36
SD	2.83	2.95	2.72	2.49

3.2 Household results regarding flood and drought mitigation measures

This section provides an empirical analysis of the household mitigation measures. The respondents chose among 13 mitigation strategies aimed at coping with changes in temperature and rainfall patterns. Eight of the original 13 strategies were considered to be negligible due to a positive response rate lower than 10 %, including practicing off-season agriculture, application of more intensive irrigation, raising less livestock in order to increase crops, raising fewer small ruminants and switching to more cattle, raising less cattle and switching to camels, raising less sheep and switching to goats, adoption of specific techniques to regenerate the necessary grass cover for the livestock, and rent or mortgage land.

The mitigation measures that recorded a positive a response rate greater than 10 % are change of crop seeds, terracing the soil or using other methods to protect against erosion, planting more trees, emigration of at least one household member, and increasing the practice of non-agricultural activities as sources of revenue (Table 6). Changing crop seeds is quite a common strategy for adapting to rainfall

changes and is widely applied in Burkinabe and Niger areas (for around 60–65 % of respondents) and, to a lesser, extent in Benin (34 %). The practice of terracing the soil to prevent erosion is mostly applied in the Beninese part of the Mékrou River basin. The planting of more trees is a common adaptation practice across the basin due to both changes in precipitation (31 %) and changes in temperature (20 %). Emigration appears as an adaptation strategy to mitigate the economic losses resulting from the impacts of changes in rainfall patterns. Around 25 % of households saw one of their members emigrating due to temperature and rainfall changes; 16.4 % of Beninese respondents stated that at least one member emigrated in the last 10 years of the study period due to rainfall changes. Finally, an important number of households, primarily in Benin (around 35 %) and in Niger (around 15 %), increasingly practice non-agricultural activities as sources of revenue to cope with the loss of income due to both rainfall and temperature changes.

3.3 Flood and drought impacts and their cost assessment

The local population of the Mékrou River basin also indicated the occurrence of extreme events during the 2-year period 2014–2015. The relatively recent occurrence of these events, some of which are still ongoing, allows for a more accurate estimation of the impacts and associated costs. Only a small percentage of the respondents (68 out of the total 660 interviewed households) stated that they had experienced any flood occurrence during the 2 years (Table 7). However, the occurrence of events differs between the three countries, with most of the events being reported in Burkina Faso (34.5 % of households affected by floods). Aligning with the frequency of reported events, the impacts of floods are proportionally more common in Burkina Faso. The most commonly reported impacts are the loss of agricultural production, damage to houses, and loss of livestock (Table 8).

The same analysis was applied for recent drought events. The vast majority (76.7 %) stated that they had not experienced any drought event during the last 2 years of the study period. However, more droughts are reported compared to floods, with 152 of the total 660 households interviewed experiencing an extreme drought event. Similarly, the occurrence of droughts is heterogeneous across the three countries. Droughts are less prominent in Niger (Table 7), where only a few droughts were reported, while a quarter of the population in Benin had experienced droughts during the last 2 years of the study period. In Burkina Faso, almost half of the households had experienced droughts during the 2-year period. The impacts of the recent drought were mostly recorded in Burkina Faso and Benin (Table 8), presenting a different profile. In Burkina Faso the impacts were exclusively manifested as losses of agricultural production, while in Benin most of the impact of the recent droughts was felt in the loss of agricultural production as well as malnutrition and loss

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Table 6. Household mitigation measures.

	Benin		Burkina Faso		Niger		Mékrou basin	
	Count	%	Count	%	Count	%	Count	%
			Change of crop seeds					
			Action taken due to temperature					
Yes	50	16.2 %	29	19.6 %	5	2.8 %	84	13.2 %
No	259	83.8 %	119	80.4 %	175	97.2 %	553	86.8 %
			Action taken due to rainfall					
Yes	110	34.0 %	99	66.9 %	110	61.1 %	319	48.9 %
No	214	66.0 %	49	33.1 %	70	38.9 %	333	51.1 %
			Terracing the soil or using other methods to protect against erosion					
			Action taken due to rainfall					
Yes	77	23.8 %	26	17.6 %	19	10.6 %	122	18.7 %
No	247	76.2 %	122	82.4 %	161	89.4 %	530	81.3 %
			Plantation of more trees					
			Action taken due to temperature					
Yes	84	27.2 %	33	22.3 %	8	4.4 %	125	19.6 %
No	225	72.8 %	115	77.7 %	172	95.6 %	512	80.4 %
			Action taken due to rainfall					
Yes	112	34.6 %	39	26.4 %	51	28.3 %	202	31.0 %
No	212	65.4 %	109	73.6 %	129	71.7 %	450	69.0 %
			Emigration of at least one household member					
			Action taken due to rainfall					
Yes	53	16.4 %	12	8.1 %	46	25.6 %	111	17.0 %
No	271	83.6 %	136	91.9 %	134	74.4 %	541	83.0 %
			Practicing more often non-agricultural activities as sources of revenue					
			Action taken due to temperature					
Yes	100	32.3 %	11	7.4 %	32	17.8 %	143	22.4 %
No	210	67.7 %	137	92.6 %	148	82.2 %	495	77.6 %
			Action taken due to rainfall					
Yes	119	36.6 %	14	9.5 %	20	11.1 %	153	23.4 %
No	206	63.4 %	134	90.5 %	160	88.9 %	500	76.6 %

of livestock. Both the flood and drought impacts recorded relate to general categories of impacts, mainly agriculture, livestock, and housing, as it was not feasible to collect more in-depth qualitative characteristics of the impacts.

The estimated flood costs to households differ among the three countries. The cost of the recent floods is highest in Burkina Faso (Table 9), where the average cost to an affected household is FCFA 334 326 (West African francs) (approximately EUR 510 in 2017). The estimated flood costs in Benin and Niger are 40 000 and FCFA 160 000, respectively. Furthermore, we observed a difficulty among the households in estimating the costs of the recent floods, especially in Benin and Niger (the less affected countries), where most of the affected households were not able to provide a cost estimation. Twenty out of 68 affected households in the basin were not able to provide a cost estimation of the floods they experienced. The average cost of the recent droughts, FCFA 256 440 (∼ EUR 391), was almost the same in Burkina Faso and in Benin (Table 9) and was lower than the average cost of the recent floods. Again, it is evident that households found it difficult to estimate the costs of the recent droughts, especially in Benin where the majority (61 out of the 152

Table 7. Experienced extreme flood events during the last 2 years (2014–2015).

	Benin		Burkina Faso		Niger		Mékrou basin	
	Count	%	Count	%	Count	%	Count	%
				Floods				
Yes	9	2.7 %	51	34.5 %	8	4.4 %	68	10.3 %
No	322	97.3 %	97	65.5 %	172	95.6 %	591	89.7 %
				Droughts				
Yes	83	25.5 %	66	44.9 %	3	1.7 %	152	23.3 %
No	243	74.5 %	81	55.1 %	177	98.3 %	501	76.7 %

Table 8. Impacts of extreme floods and droughts to the households.

	Benin	Burkina Faso	Niger	Mékrou basin
	Count	Count	Count	Count
		Impacts of floods		
Damage to the house	3	24	5	32
Loss of agricultural production	8	44	7	59
Injury or death of a household member		1	3	4
Loss of livestock		16	4	20
		Impacts of droughts		
Loss of agricultural production	74	66	3	143
Malnutrition of at least one household person	41	4	2	47
Loss of livestock	20	4	3	27

Table 9. Estimated costs of the recent flood and droughts (in FCFA).

	Mékrou basin	Benin	Burkina Faso	Niger
		Costs of floods		
Mean	324 563 (∼ EUR 495)	40 000	334 326	160 000
SD	373 159		378 071	
		Costs of droughts		
Mean	256 440 (∼ EUR 391)	262 184	252 803	0
SD	324 224	257 676	362 150	0

households) of the affected households were not able to provide a cost estimation. Regarding the geographical differentiation of the cost of both floods and droughts, heterogeneity is observed among the three countries but not within the countries where costs are homogenous among the selected villages and towns. Also, the small sample of the households affected by floods and droughts is insufficient for statistical aggregation to the total population of the basin.

3.4 An econometric analysis to identify variables that influence the costs of floods and droughts

In addition to the statistical estimation of the cost of floods and droughts, two econometric models were developed to provide an analysis of costs based on socioeconomic and other relative factors. A wide series of independent variables of the household, such as socioeconomic conditions and mitigation measures, was used to find the determinants of the cost of extreme events and to analyse the cost of floods and droughts. Using several regression models and a combination of independent variables, two models were set up that exclusively included statistically significant independent variables (p value less than 0.05, and in one case slightly higher than 0.05 but less than 0.1). Table 10 presents the total of the independent variables, including their scaling and correlation. The latter is important for the coherence of the multivariate models, since low correlation among the independent variables excludes the existence of multicollinearity.

Regarding floods, the multivariate regression model in Table 11 includes the self-stated economic status (ECONSTAT) of households as an independent variable and as a qualitative alternative to household income. The model reveals a strong economic status effect, meaning that the richer the household, the higher the economic impact of floods. The negative sign is due to the structure of the variable scaling (where 1 represents rich and 5 represents significantly poorer economic conditions than the other households). Two of the main flood impacts, loss of crop productivity (CropProdLoss) and loss of livestock (LivestockLoss), were also included in the model as independent variables and were found to be significant. According to the multivariate regression model, the average cost of floods per household during the flood events of the last 2 years of the study period (2014–2015) was equal to EUR 390.92. In order to avoid problems of multicollinearity, correlation among the independent variables was tested. The calculated Pearson's R values, all be-

Table 10. Selected independent variables for modelling costs of floods and droughts.

Variable	Scaling	Correlation
ECONSTAT	1 – rich; 2 – relatively rich; 3 – average; 4 – below average; 5 – much worse than average	CropProdLoss: −0.0786 LivestockLoss: −0.134
CropProdLoss	0 (no impact), 1 (impact)	LivestockLoss: −0.017
LivestockLoss	0 (no impact), 1 (impact)	PRODCROP: 0.212
PRODCROP	Numerical value	

Table 11. Costs of floods – multivariate linear regression model.

Number of obs = 48; R-sq: 0.4828	F test: 7.842		
Independent variables	Coef.	SE	$P > z$
ECONSTAT	−1285˙48.5	47 850.09	0.01
CropProdLoss	287 269.9	129 224.5	0.031
LivestockLoss	359 272.4	92 753.99	0
_cons	429 595.2	225 058.3	0.063
Cost estimate/household	256 441 (FCFA)	390.92 (EUR)	

Table 12. Costs of droughts – multivariate linear regression model.

Number of obs = 98; R-sq: 0.1907	F test: 11.196		
Independent variables	Coef.	SE	$P > z$
PRODCROP	14.08	3.64	0
LivestockLoss	137 261.8	74 243.4	0.068
_cons	130 367.5	39 952.2	0.002
Cost estimate/household	324 563 (FCFA) 495 (EUR)		

low the 0.3 threshold, suggest a low correlation among the independent variables.

Similarly, a multivariate regression model was applied to analyse the costs of droughts (Table 12). The independent variable related to loss of livestock was found to have a strong effect in this model too. However, drought costs are found to significantly depend on the total crop production of the households (PRODCROP). According to this regression model, the estimated cost of droughts per household that experienced drought events during the last 2 years of the study period (2014–2015) was EUR 494.76. Similarly low correlations were detected among the independent variables.

4 Discussion and conclusions

This paper combines the results of a household survey and climate data analysis to assess floods, droughts, and climate variability in the Mékrou River basin in West Africa. The opinions and perceptions of household representatives revealed strong climate variability over a 10-year period (2006–2015). It is worth mentioning that 83 % of the population noticed a delayed onset of the rainy season during this period. In addition, 91 % of the population also observed an early end of the wet season. Moreover, 88.5 % of the respondents reported a general reduction in precipitation during the 10-year period under consideration, and 75.9 % reported an increase in the magnitude and frequency of extreme heat events. This tendency is partially confirmed by the analysis of climatic variables, mainly based on precipitation and temperature data. The findings of the analysis confirmed the increase in both the frequency and magnitude of heat waves in the study area. The climatic variability was also found to be noticeably high, but the Mann–Kendall analysis failed to find statistically significant trends in the precipitation patterns. It was not possible to clearly identify a shift in the intra-annual temporal distribution of precipitation, as there was no indication of a slightly delayed onset nor an early end of the rainy season.

The survey-based findings revealed a substantial difference between the occurrence of floods and droughts. With regard to droughts, 86.8 % of the population reported that dry periods were more frequent during the 10 years from 2006 to 2015, while 23.3 % experienced an extreme drought event during the last 2 years (2014–2015), resulting in 3.93 extreme drought events on average. Fewer flood events than drought events were reported by the local population. More

than 60 % of the respondents stated that flood frequency did not change during the period 2006–2015, and only 10.3 % of the population experienced an extreme flood event during the period 2014–2015 (1.69 extreme flood events on average per household). The perceptions of the local population were confirmed by the climatic factors regarding flood events. An analysis of extreme precipitation in the past 30 years did not report a significant increasing trend in the occurrence of flood events. Similar conclusions, but this time contrary to the impressions of the local population, were derived from the analysis of dry periods. This difference between perceived occurrence and observed droughts could be explained by the misperception of the local population confounding the observed increasingly frequent heat wave events with more frequent droughts. However, an analysis of the meteorological (SPI-3) and agricultural (SPI-6) drought indicators confirmed the occurrence of a number of dry periods that could be in line with those reported by the local population in the portion of the basin located within the borders of Benin and Niger. However, the analysis of the SPI failed to find any significant dry periods in the Beninese portion of the Mékrou River basin.

The household survey analysis reported important findings regarding the measures adopted by the households of the Mékrou River basin to mitigate floods and droughts. From a list of options, the most significant household mitigation measures were identified as being: changing crop seeds, planting more trees, and increased practice of non-agricultural economic activities, while, especially in Niger, a considerable part of the population emigrated due to the loss in agricultural production caused by the reduced rainfall. The findings regarding the impacts of floods and droughts and their costs are also interesting. For those households that experienced an extreme flood event during the period 2014–2015, the most frequent impacts were reported to be crop production losses, damages to houses, and loss of livestock. The loss of crop production, malnutrition, and the loss of livestock were the most important impacts of extreme droughts. In addition, the total cost per household of the impacts of extreme floods and droughts was estimated. The cost assessment is two-fold, based on the sample estimations and the application of two linear multivariate regression econometric models. The average cost of flood events in the period 2014–2015 was estimated at EUR 495 per affected household, based on the average declared losses. The average cost of extreme droughts was EUR 391 per household. This study confirmed the difficulty of estimating the costs of natural hazards at the household level, even in the case of recent events. A considerable percentage of household representatives (27 % for floods and 38 % for droughts) were not able to provide an estimation of the costs of the extreme events that they recently experienced.

Regarding the methodological approach of this work, the combination of the household survey data analysis with the study of the climatic variables could provide an integrated assessment of floods and droughts, especially in cases such as the Mékrou River basin, where access to reliable information is very limited. The survey approach, in particular, could provide data at household level that could be used for a detailed qualitative and quantitative assessment of natural hazards, such as floods and droughts. Potential limitations of this approach are mainly the information biases and misperceptions of the local population, which could influence the objectivity of their responses. Furthermore, such a survey approach depicts the opinions within a specific time frame and, therefore, should be periodically repeated to better validate the findings. This would require increased financial and human resources. The major potential benefit of this approach is that it provides information to support decision-makers and local governments, leading to the more effective and efficient design of flood and drought mitigation policies and measures. Most often, natural hazards risk mitigation measures and policies use either climate modelling tools or socioeconomic analyses, but rarely combine both. In developing countries where information is limited, such a coupling approach could integrate local characteristics and perceptions into natural hazard planning policies in order to provide more efficient mitigation measures. More specifically, such an approach could be used by state and local authorities to design risk mitigation and prevention measures in the framework of transboundary river basin management plans or even design climate adaptation strategies combining climate and socioeconomic analysis while structuring national adaptation programmes of action (NAPAs).

The Supplement related to this article is available online at https://doi.org/10.5194/nhess-18-1279-2018-supplement.

Author contributions. VM, CD, and CCM designed the household survey and analysed the data. FF, IA, MP, LM, and AA analysed the climate data. VM, CD, FF, and IA prepared the first draft of the manuscript. All authors discussed the results and commented on the manuscript at all stages.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue "Damage of natural hazards: assessment and mitigation". It is not associated with a conference.

Edited by: Thomas Thaler
Reviewed by: three anonymous referees

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