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Frequency Analysis and New Cartography of Extremes Daily Rainfall Events in Côte d'Ivoire

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Abstract: The extreme rainfalls are meteorological events that cause much damage and many casualties. In a disrupted climate context by human activities, it is necessary to consider the probability distribution of rainfall extremes to protect the population. In this context, 43 rainfalls stations over the period 1947 to 1993 were analyzed. Frequency analysis has shown that Gumbel distribution and the Lognormal distribution fit well with a series of annual maximum daily rainfall. It was also shown a link between the probability distribution of annual maximum daily rainfall and climate patterns. Indeed, none of them do not obey a specific rainfall. The present study has also proposed new maps of daily annual maximum rainfall for return periods of 5, 10, 20 and 100 years.

Key words: Extreme rainfall, frequency analysis, mapping, hydrological design, Côte d'Ivoire

INTRODUCTION

The Côte d'Ivoire is located in West Africa and is characterized by humid equatorial climates and dry tropical climates (Fig. 1). The West Africa has experienced a decrease in annual rainfall since 1970 (Goula *et al.*, 2006a). In certain areas of West Africa, the annual rainfalls have decreased on average from 20 to 40% (Goula *et al.*, 2009). The flows decreased from 10% in wetlands and sub-wet and 30% in the Sahel (Goula *et al.*, 2006b). Despite this climate context, Côte d'Ivoire as well as many countries in the tropical areas (Burkina Faso, Mali, Senegal, Niger and Ghana) are facing serious flooding problems. The flood risk assessment is based on knowledge of extreme precipitation. Other factors such as land cover and land slope are also determinants. The analysis of maximum rainfall can be from very different perspectives but complementary. The statistical approach (frequency analysis) has often been used in major studies on extreme rainfall, which have been realized on the Cote d'Ivoire (Soro *et al.*, 2008), the other states of Western and Central Africa (CIEH, 1985; Puech and Chabi-Gonni, 1984) and Nigeria (Oyebande, 1982). Many studies have been devoted worldwide (Koutsoyiannis and Baloutsos, 2000; Gellens, 2002; Zalina *et al.*, 2002; Ramon *et al.*, 2005; Sisson *et al.*, 2006; Zahar and Laborde, 2007; Twardosz, 2009; Bodini and Cossu, 2010).

The present study constitutes the second phase of the study of extreme rainfall in Côte d'Ivoire. It aims to analyze a series of annual maximum daily rainfall available in the country beyond the periods used in previous studies. Indeed, the statistical study of extreme values has always been conducted in a conventional manner using the Gumbel distribution. Recently, several studies (Coles and Perrichi, 2003; Koutsoyiannis, 2004; Bacro and Chaouche, 2006; Goula *et al.*, 2007) have challenged the predominance of the Gumbel distribution for the quantification of risk associated with extreme rainfall. Some studies have shown that the probabilities distributions characterizing the floods seem to have the tails of distributions heavier than the Gumbel distribution (Farquharson *et al.*, 1992; Turcotte, 1994). Other studies (Wilks, 1993; Coles and Perrichi., 2003) extended the skepticism for the Gumbel distribution in the case of precipitation, showing that it greatly underestimated the extreme values.

This disadvantage is very important for the design of engineering structures. The stakes in the debate between the choice of the Gumbel distribution or any other distributions (GEV, Lognormal, Pearson III, Log-Pearson III) is important because it is directly related to the reliability of hydraulic structures and roads. Also, is it considered necessary to verify, taking into account these new data, the validity of this distribution of probability (Gumbel) on the entire territory. The aim of this paper is to provide a better estimation of design rainfall order to achieve a new mapping of extreme daily rainfall.

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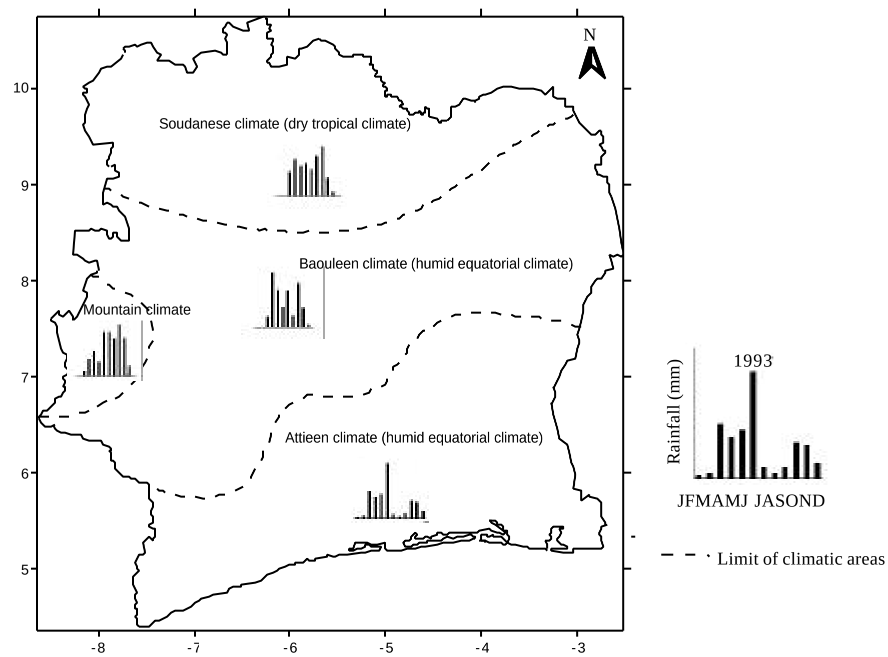

Fig. 1: Principal climatic areas of the Côte d'Ivoire

MATERIALS AND METHODS

Data rainfall used: Daily rainfall data form 34 pluviometric stations located in Côte d'Ivoire have been considered in this study. Their geographical locations are shown in Fig. 2. Daily data form these stations were selected because they are of a high quality and are most complete. The data have been provided by Hydrology Laboratory of Institute of Research for Development. The record lengths of each rainfall data series varied form a minimum of 36 years to over 47 years and cover the period from 1947 to 1993.

Methodology of the frequency analysis: Frequency analysis is a statistical approach commonly used in hydrology to relate the magnitude of extreme events to a probability of occurrence. The main objective of frequency analysis is to infer the probability of exceedence of all possible events, in the case the extremes daily rainfall, from observed values (a sample parent population).

Test of independence, stationarity and homogeneity: All series obtained must comply with the hypothesis of homogeneity, stationarity and randomness. To verify these hypotheses three non parametric tests were used. The homogeneity test of Wilcoxon (1945) allows to carry out comparisons between two subsamples and to check if the averages of the two subsamples are significantly different (Baudez *et al*., 1999).

The Kendall trend test (Kendall, 1975) is based on the correlation between the ranks of a time series and their time order (Yue and Pilon, 2004). It is a rank-based nonparametric method used to detect the trends in the series. Non-parametric trend detection methods are less sensitive to outliers (extremes) than are parametric statistics such as Pearson's correlation coefficient (Wang *et al*., 2008). As the Kendall test requires independent series, serial dependence was also tested using the non-parametric Wald-Wolfowitz test (Wald and Wald-Wolfowitz, 1943).

Fitting of distribution functions and estimation methods: The first step is to fit a distribution function to each group comprised of the data values for a specific duration. Random hydrological variables that are extremes, such as maximum rainfall and floods are described by several extremes value distributions (Overeem *et al*., 2008; Huard *et al*., 2009) or often Lognormal distribution (Soro *et al*., 2010). For this study, five statistical distributions were retained (Table 1). Several formulas exist to calculate this probability. In this study, the empirical probability chosen for this statistical analysis is that of Hazen. In the humid tropical area, it has been used by several authors (Puech and Chabi-Gonni, 1984; Goula *et al*., 2007). The distribution parameters are determined by the maximum likelihood method except the log Pearson III, which required the use of methods of weighted moments.

Adequacy testing: There are different methods to compare and select the distribution that best fits a given sample. It

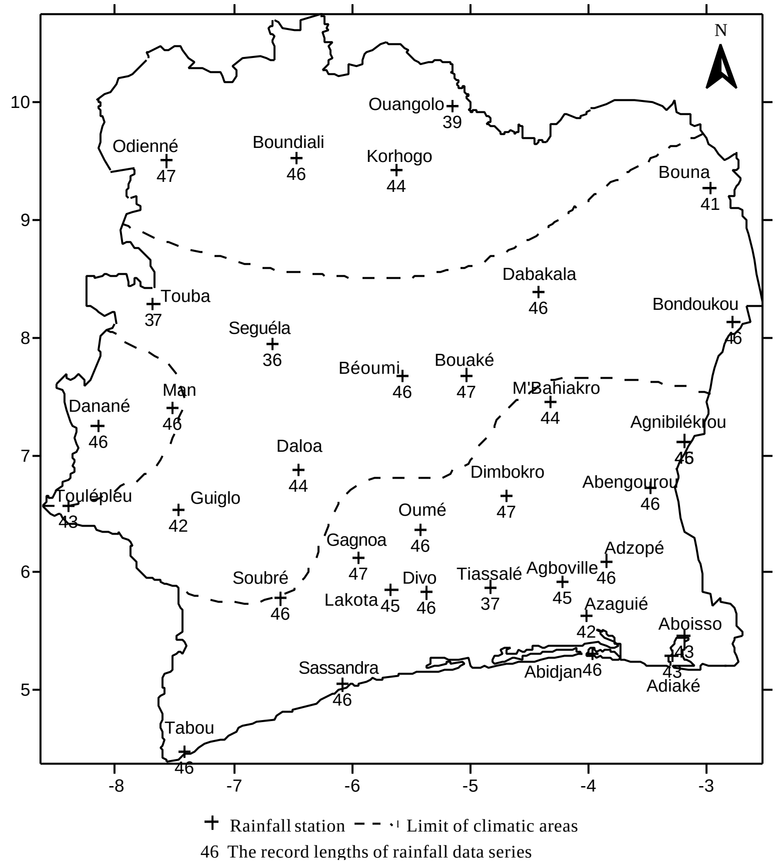

Fig. 2: Geographical locations of raingauges and the record lengths of series

Table 1: Probability distribution functions used

Name	Probability density function	Parameters
Generalized extreme value	$f(x)=\frac{1}{\alpha}\left[1-\frac{k}{\alpha}(x-u)\right]^{1/k-1}\exp\left\{-\left[1-\frac{k}{\alpha}(x-u)\right]^{\frac{1}{k}}\right\}$	u, α, k
Gumbel	$f(x)=\frac{1}{\alpha}\exp\left[-\frac{x-u}{\alpha}-\exp(-\frac{x-u}{\alpha})\right]$	μ, α
Lognormal 2	$f(x)=\frac{1}{x\sigma\sqrt{2\pi}}\exp\left[-\frac{(\ln x-\mu)^2}{2\sigma^2}\right]$	μ, σ
Pearson III	$f(x)=\frac{\alpha^{\lambda}}{\Gamma(\lambda)}(x-m)^{\lambda-1}e^{-\alpha(x-m)}$	α, λ, m
Log pearson III	$f(x)=\frac{\alpha^{\lambda}}{\Gamma(\lambda)}(\ln x-m)^{\lambda-1}e^{-\alpha(\ln x-m)}$	α, λ, m

is possible to visually examine the quality of the fit between the empirical probability exceedance and a distribution, both plotted on probability paper. However, this method is based only on the judgment of the hydrologist and can be sometimes subjective.

For this study, two selection criteria were used, both based on the likelihood function: The Akaike (1974) and the Bayesian (Schwarz, 1978) information criteria, respectively given in equation Eq. 1 and 2:

$$AIC = -2\log(L)+2k \quad (1)$$

$$BIC = -2\log(L)+2k\log(N) \quad (2)$$

where, AIC is the Akaike information criterion; BIC is the Bayesian information criterion; L is the likehood function; k is the number of parameters; N is the sample size.

Equation 1 and 2 both include k, the number of parameters. Thus, parsimony is taken into account when selecting the best distribution using these two criteria.

The best fit is the one associated with the smallest BIC and AIC values (Rao and Hamed, 2001). The BIC criterion tends to penalize three parameter distributions more severely than the AIC and sometimes the optimal fitted distribution differs form one criterion to another. In the case of different selections by the AIC and BIC criterion, the distribution identified by the BIC criterion was selected to emphasize parsimony.

RESULTS AND DISCUSSION

Hypothesis testing: Application of the Kendall test showed that there was no trend in the annual maximum daily rainfall with a risk error of 5% (significance level of 0.05) except for stations of Adzopé, Agboville and Adiaké where, the risk is 1% (significance level of 0.01). The Wilcoxon test shows that the average of the two sub-samples is equal at the significance level of 5%. This indicates that the rainfall observations are from the same population. The Wald test indicates that the rainfall observations are independent with a significance level of 5%; therefore there is no link between successive observations.

Fitting of probability distributions: Figure 3a-d present the empirical probability of some series of annual maximum rainfall. From the graph (Fig. 4), it is very hard to select the best probability distribution. The criteria of comparison was used to solve this problem by choosing the distribution with the lowest values of BIC and AIC. In the maximum precipitation serie analyzed, the lowest AIC and BIC was achieved by the Gumbel distribution (Table 2). Figure 5a-d depict the Gumbel, Pearson III, Generalized Extreme Value and Lognormal distributions fitted by Maximum Likelihood method for annual maximum daily rainfall of four stations.

Area of validity (distribution of probability): Overall, the probability distributions of annual maximum daily rainfall do not obey a specific climate regime (Fig. 6). The

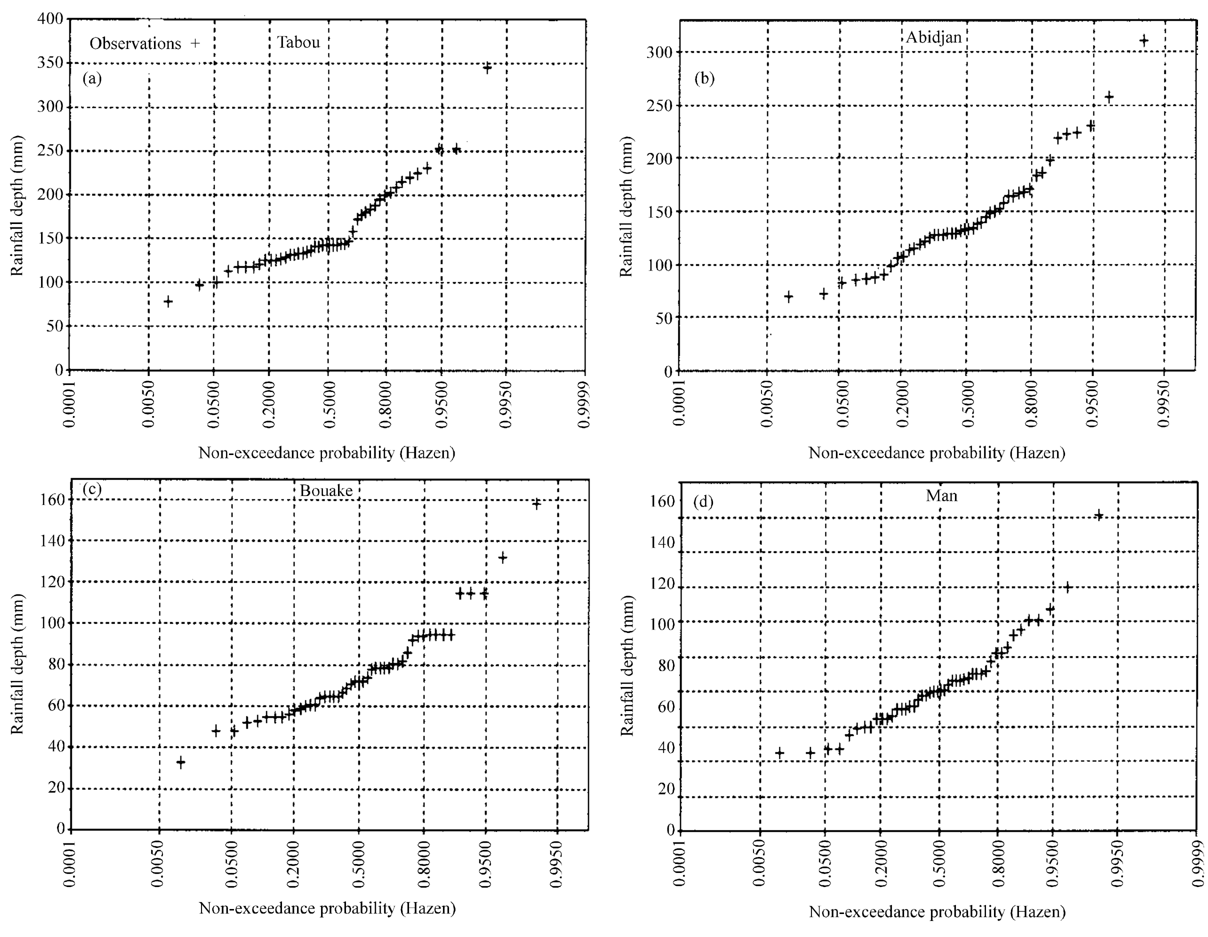

Fig. 3: Empirical distribution for the annual maximum series of Tabou, Abidjan, Bouaké and Man

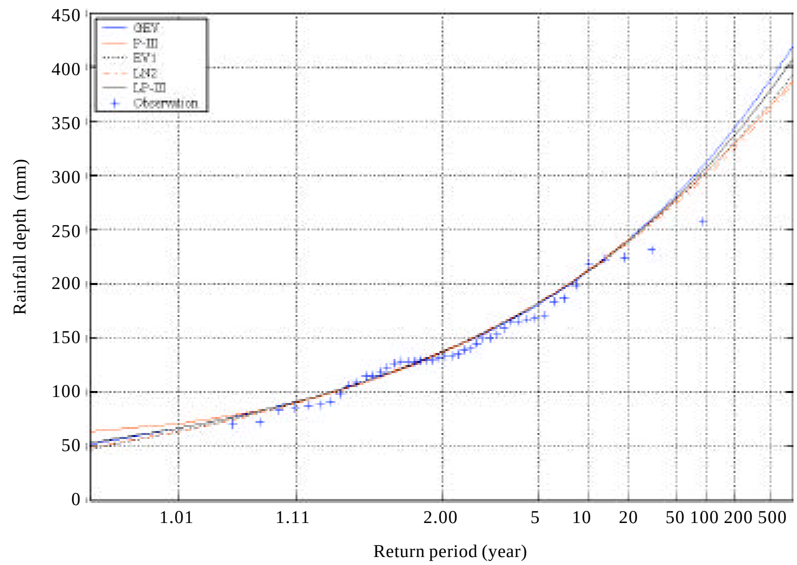

Fig. 4: Generalized Extreme Value (GEV), Pearson III (P-III), Gumbel (EV1), Lognormal (LN2) and Log Pearson III (LP-III) distributions fitted by the method of Maximum Likelihood method for the annual maximum daily rainfall series of Abidjan

Table 2: The Akaike (AIC) and the Bayesian (BIC) information criteria calculated for the annual maximum daily rainfall series of Abidjan

Probability distribution	AIC	BIC
Gumbel (EV1)	484.57	488.23
Lognormal (LN2)	484.60	488.26
Pearson type III (P-III)	486.20	491.69
Log-Pearson type III (LP-III)	486.45	491.94
Generalized Extreme Value (GEV)	486.51	492.00

Generalized Extreme Value (GEV) distribution is best suited to Tiassalé, Soubré and Agboville regions. The Pearson III distribution well fits the extreme North-East and in the region Beoumi. The Lognormal distribution applies well to the South-East, West (Danane-Guiglo), in the Center (M'Bahiakro-Dimbokro). This distribution is appropriate to describe the extreme rainfalls of north regions (Ouangolo, Korhogo and Odienné). The Gumbel distribution applies in many regions of South-West (Tabou, Daloa Toulépleu). We find this distribution to the East (Abengourou and Bondoukou). The results at level of these stations converge with other recent studies such as those by Goula *et al*. (2007).

Estimation and comparison of quantiles: The quantiles obtained (Table 3) were compared with those of previous study on the Côte d'Ivoire. It was chosen 10 stations which have been simultaneously in previous studies and the current study. At stations Odienné, Gagnoa and Dimbokro (Table 3), we note that the Gumbel distribution was not suitable for the estimation of extreme quantiles. The calculations with the lognormal distribution give very high relative errors (Table 4).

These errors vary between 38 and 5.5% for rainfall return period of 100 years (P_{100}), between 34 and 4.6% for rainfall return period of 50 years (P_{50}), between 24 and 2.4% for rainfall return period of 10 years (P_{10}) and between 18 and 1.3% for rainfall return period of 5 years (P_5). The quantiles were overestimated with the Gumbel distribution by Brunet-Moret (1967). By cons at Station Soubré, the relative errors vary between -28.9 and -4.32% for P_{100}, P_{50}, P_{10} and P_5. The negative sign assigned to different percentages shows that the Gumbel distribution used for the previous study underestimated the quantiles from the GEV distribution used in this study. For stations of Abengourou, Adzopé, Bondoukou, Bouake and Man, the current study confirmed the Gumbel distribution. However, the errors are not zero. This indicates that the current design tools are better developed than those used by Brunet-Moret (1967).

Mapping daily record rainfall: The mapping of the different quantiles for return periods for all stations was conducted. Figure 7a-d show those of the return periods 100, 50, 10 and 5 years. Isohyets vary greatly in a South-North to latitude 6°N. This area corresponds to the

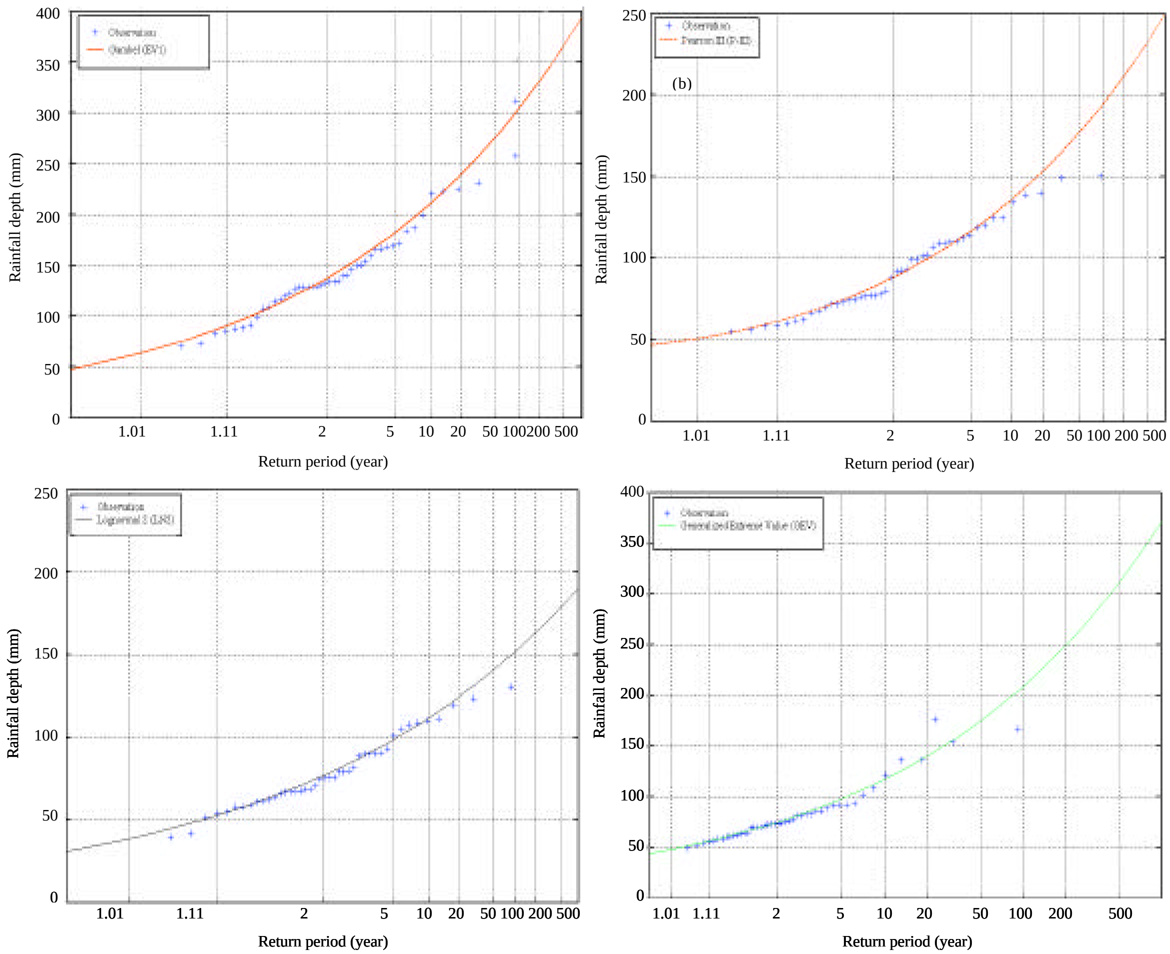

Fig. 5: Gumbel (EV1), Pearson III (P-III), Log Normal (LN2) and Generalized Extreme Value (GEV) distributions fitted by Maximum Likelihood method for annual maximum intensities rainfall series of (a) Abidjan, (b) Béoumi, (c) Korhogo and (d) Soubré

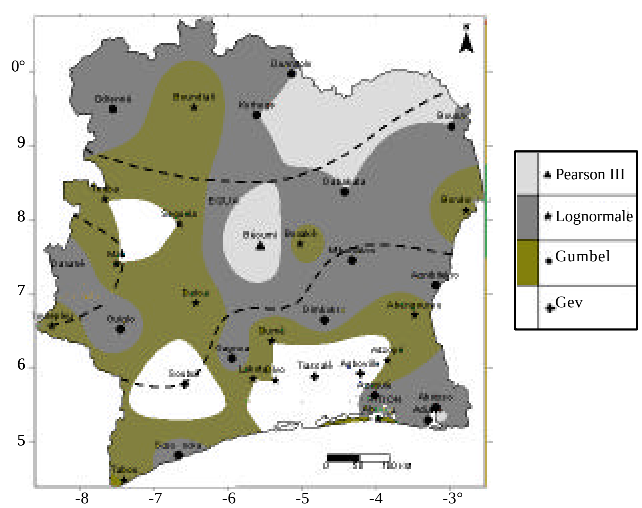

Fig. 6: Delimitation of validity of probability distribution

Table 3: Parameters of distributions probability and quantile values (mm) estimated for return periods of 5, 10, 50 and 100 years

Stations	Probability distribution	Parameters a	α	σ	υ	μ	k	m	Quantiles (mm) P_{100}	P_{50}	P_{10}	P_5
Agboville	GEV	21.1		62.9		0.2			120	115	99	89.1
Soubré	GEV	15.7		68.4		0.3			219	181	118	97.8
Tiassalé	GEV	22.5		72.2		0.4			122	118	106	98.0
Abengourou	Gu	17.9		69.4					152	139	110	96.3
Abidjan	Gu	38.8		122.9					301	274	210	181.0
Adzopé	Gu	17.2		75.7					155	143	114	101.0
Bondoukou	Gu	13.1		64.9					125	116	94.5	84.6
Boundiali	Gu	17.7		81.2					162	150	121	108.0
Daloa	Gu	21.5		73.4					172	157	122	106
Divo	Gu	17.8		71					153	140	111	97,7
Lakota	Gu	15.8		69.2					142	131	105	92,9
Man	Gu	20.6		72.1					167	152	118	103
Oumé	Gu	21.5		69.1					168	153	117	101
Seguela	Gu	19.2		70.1					158	145	113	98,9
Tabou	Gu	36.2		137.7					304	279	219	192
Touba	Gu	20.8		73.4					169	155	120	105
Toulepleu	Gu	22.6		77.8					182	166	129	112
Bouaké	Gu	18.3		65.9					150	138	107	93,5
Aboisso	Ln		0.3		4.6				236	214	162	139
Adiaké	Ln		0.3		4.8				290	263	201	172
Agnibilekro	Ln		0.3		4.3				170	155	118	102
Azaguié	Ln		0.3		4.4				179	164	128	112
Bouna	Ln		0.3		4.3				151	138	109	94,5
Dabakala	Ln		0.3		4.4				154	142	114	101
Danané	Ln		0.3		4.7				207	192	156	138
Dimbokro	Ln		0.3		4.2				140	129	102	89,4
Gagnoa	Ln		0.3		4.3				135	125	102	90,3
Guiglo	Ln		0.3		4.5				160	150	124	111
Korhogo	Ln		0.3		4.3				151	139	111	97,8
M'bahiakro	Ln		0.3		4.3				138	128	106	94,4
Odienné	Ln		0.3		4.4				160	149	120	106
Ouangolo	Ln		0.3		4.3				137	128	104	93,1
Sassandra	Ln		0.3		4.8				305	276	208	177
Béoumi	PIII	0.03					1.4	53.8	212	190	139	117

Table 4: Comparison of quantiles (mm): Brunet Moret (1967) and the current study for return periods of 5, 10, 50 and 100 years

	Previous study (Brunet-Moret (1967)					Current study					Errors (%)			
Stations	Law	P_{100}	P_{50}	P_{10}	P_5	Law	P_{100}	P_{50}	P_{10}	P_5	P_{100}	P_{50}	P_{10}	P_5
Abengourou	Gu	150.9	139	110	96.4	Gu	152	139	110	96.3	-0.72	-0.22	-0.36	0.1
Adzopé	Gu	153.8	142	114	101.0	Gu	155	143	114	101	-0.77	-0.70	0.0	0.3
Bondoukou	Gu	124.8	116	94.5	84.8	Gu	125	116	95	84.6	-0.16	-0.17	0.0	0.2
Bouaké	Gu	149.9	137	107	93.7	Gu	150	138	107	93.5	-0.07	-0.58	0.3	0.2
Bouna	Gu	152.3	139	108	93.7	Ln	151	138	109	94.5	0.90	0.80	-1.01	-0.8
Dimbokro	Gu	147.7	135	104	90.6	Ln	140	129	102	89.4	5.50	4.60	2.4	1.3
Gagnoa	Gu	172.6	131	103	90.8	Ln	135	125	102	90.3	28.00	4.70	1.3	0.6
Man	Gu	165.3	151	118	103.0	Gu	167	152	118	103	-1.02	-0.46	0.0	-0.1
Odienné	Gu	220.5	199	149	125.0	Ln	160	149	120	106	38.00	34.00	24.0	18.0
Soubré	Gu	155.8	143	113	98.9	GEV	219	181	118	97,8	-28.90	-21.00	-4.32	1.1

equatorial system of transition under the influence of the Atlantic Ocean and West African Monsoon. The highest values of centennial quantiles (return period of 100 years) are estimated on the coastal stations Tabou (304 mm), Sassandra (305 mm), Abidjan (301 mm) and Adiaké (290 mm). From latitude 6°N to latitude 11°N, the isohyets vary likeky in a South-West and a North-East. This monotony is broken between the latitudes 6.5° and 7.5° N especially in the mountainous region and around the lake Kossou. The highest values of quantiles in the region of Man highlight the role of mountains on rainfall extremes. Indeed, the mountains of western Côte d'Ivoire are advancing a broad eastern mountain range centered on Guinea and called the backbone of Guinea. The highlights are aligned North-West to South-East the Fouta Djallon (1515 m), Mount Loma (2100 m) and Mount Nimba (1750 m) lie at the intersection of Cote d'Ivoire. This vast mountain range can contribute to the rainfall amount by opposition to the penetration of normal monsoon in the continent by

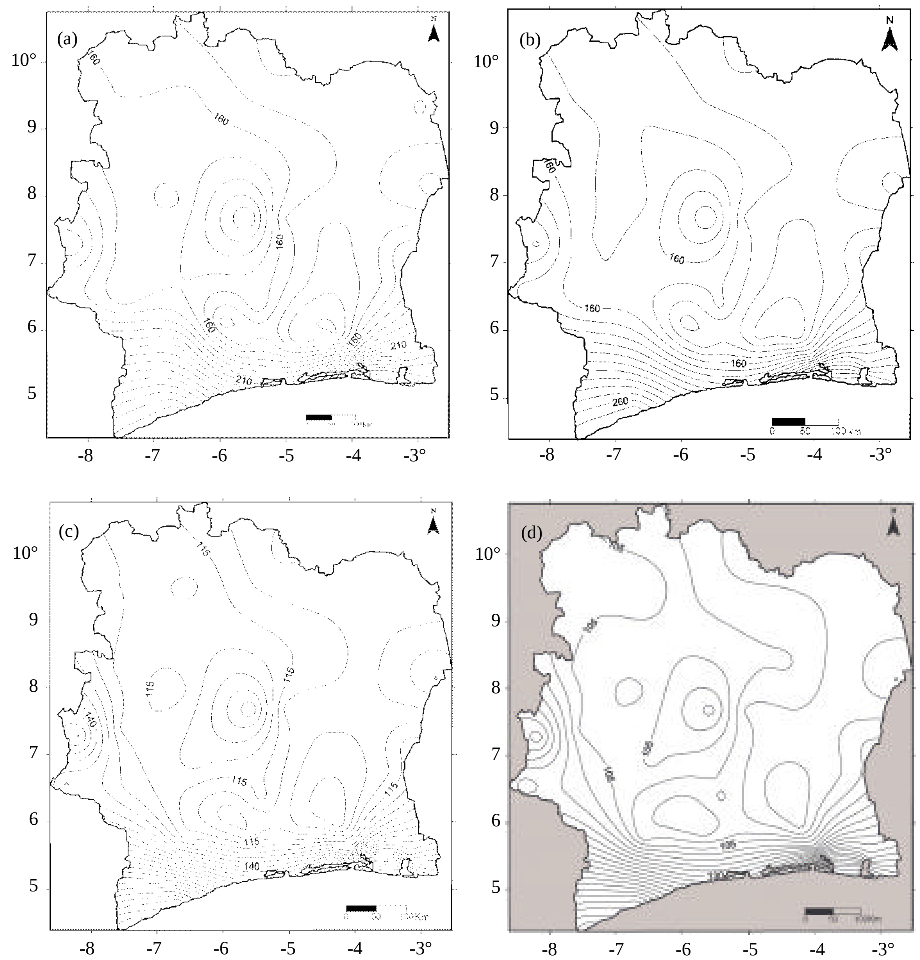

Fig. 7: Isohyet of annual maximum daily rainfall for return periods of 100 (a), 50 (b), 10 (c) and 5 years (d)

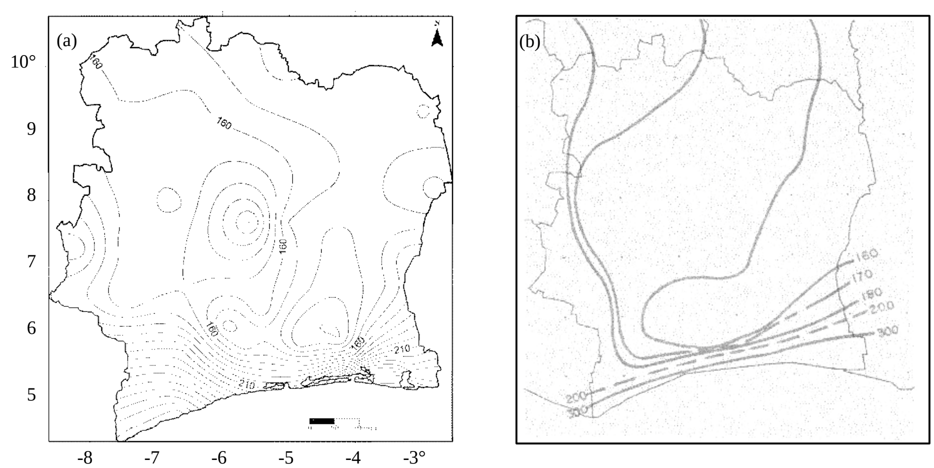

Fig. 8: Comparison of decennial isohyets (10 years): (a) present study, (b) previous study (CIEH, 1985)

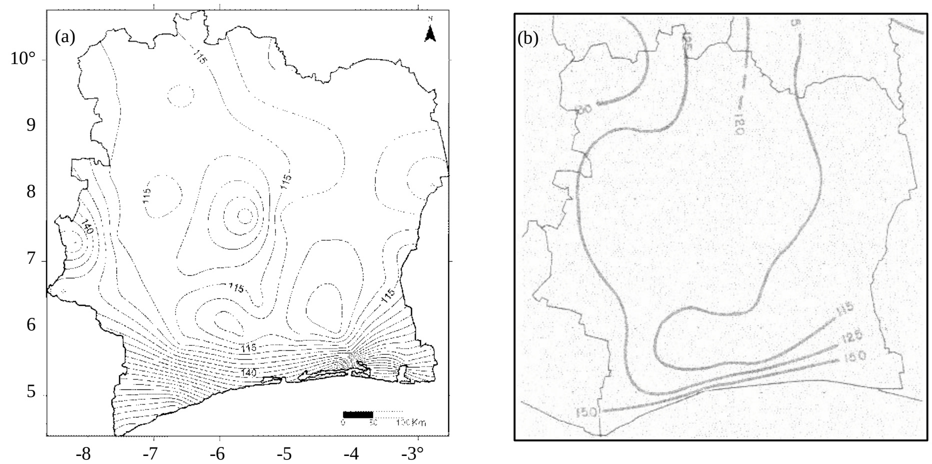

Fig. 9: Comparison of decadal isohyets (100 years): (a) present study and (b) previous study (CIEH, 1985)

promoting and uplift of air masses over these regions. Thus, the foehn effect may partly explain in the influence of this factor (orography) on rainfall extremes. Other studies have shown the influence of the orography (Kieffer and Bois, 1997; Zahar and Laborde, 2007). At the region of Beoumi, daily rainfall return period of 100 years is 212 mm. This value can be explained by the presence of Lake Kossou. The intense evapotranspiration in this equatorial climate transition may cause heavy rains in this area. The low quantiles values are observed stations around Gagnoa, Lakota, Tiassalé, Agboville and Dimbokro (Table 3). In these areas, quantiles vary between 120 and 142 mm for a return period of 100 years. It is also noted low quantile values at stations of Abengourou and Agnibilékrou in the East.

Comparison isohyets: The decennial and centennial isohyets of daily rainfall developed in this present study were compared to those currently used for the design of hydraulic structures in Côte d'Ivoire entirely (Fig. 8a, b). It appears a significant difference between isohyets proposed by the CIEH and those of the present study. Indeed, the isohyet proposed by the CIEH does not cover the entire Ivory Coast. Moreover, these isohyets are widely spaced compared to those in this study. At the level of centennial daily rainfall, the isohyet (300 mm) includes only the Tabou area and an infinite part of the Southeast, while covering the entire coastal strip of the map at CIEH. The isohyet (200 mm) around the mountainous region of Man appears in the map proposed by the CIEH. At the level of daily rainfall decennial isohyet (120 mm) could not be traced by the CIEH (9a-b).

CONCLUSION

The study of extreme rainfall events lets start an update of previous studies with daily series ranging from 1947 to 1993. Frequency analysis has shown that Gumbel distribution and the Lognormal distribution fit well with a series of annual maximum daily rainfall.

The GEV fits well with data sets of Agboville and Soubré Tiassalé stations. The Pearson III distribution fits well to the series of extreme rainfall of Beoumi. It was also shown a link between the probability distribution of annual maximum daily rainfall and climate patterns. The present study has also proposed new maps of annual maximum daily rainfall.

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