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Research article

Estimation of the return periods of maxima rainfall and floods at the Pra River Catchment, Ghana, West Africa using the Gumbel extreme value theory

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ABSTRACT

The Pra river catchment in Ghana is adversely affected by perennial flooding from high-intensity rainfall events. To aid in flood management at the catchment, the Gumbel extreme value distribution has been used to estimate the return periods of maxima rainfall, flood, and consecutive dry and wet days (CDD and CWD) for a period of 5 to 100 years. The results revealed an expected increase in maxima rainfall, CDD and CWD. Maxima rainfall favours the south of the catchment while the CDD decreases northward. Furthermore, an increase in the magnitude of CWD observed at the centre of the catchment had a maximum of approximately 30 days for the 100 year return period, while lower flood volumes had a higher recurrence of 50% to 100% for 1 to 2 year return periods. The inclusion of a projected increase in anthropogenic activities and climate factors at the catchment will slightly affect the magnitude of these variables for the various return periods. Nonetheless, the findings in this study will be of essential input to policy implementation of the Integrated Water Resource Management Plan for river catchments in Ghana, West Africa.

1. Introduction

Changes in the intensity, amount and duration of rain rates have serious implications with noticeable impacts in sectors such as agriculture, water resource management and flood control (Alam et al., 2018). The prolonged absence of rains may result in increasing dry spells which do not sustain crop and animal production, whereas an increase in rains likely favours agriculture but can exacerbate flooding events. Flooding in the Guinea coast of West Africa has worsened over the past years with accompanying worse effects due to high intensity rains coupled with poor infrastructure and drainage systems. Perennial floods and its impacts could be reduced by predicting the maxima rainfall and its intensity. This step is necessary for improving flood planning, design and management of hydraulic structures such as dams and stormwater drainage systems (Krishna and Veerendra, 2015; Vivekanandan, 2017; Alam et al., 2018).

Frequency analysis provides a suitable means for predicting hydro-meteorological parameters in both space and time, and this involves the estimation of the probability of occurrence of a specified event (Bhagat, 2017). The maximum rainfall and flood depths for various selected return periods are estimated from frequency analysis, for example, the Gumbel probability distribution (Raes, 2004; Mukherjee, 2013). The Gumbel distribution has been used to estimate 1-day and 1-hour maximum rainfall at the Dhaulakuan rain gauge station (Vivekanandan, 2017) and also for various return periods of 1 to 5 days maximum rainfall (Sasireka et al., 2019) in India. Over the Niger Delta in Nigeria, the Gumbel is ascertained as a better distribution for rainfall analysis and useful for the region's flood prediction (Okeke and Ehiorobo, 2017). In addition, the Gumbel distribution has successfully modelled the flood frequency of Nyanyadzi River (Mujere, 2011). However, in data-scarce regions, it is necessary to obtain reliable substitutes for flood analysis, for example, the use of well-calibrated rainfall-runoff models. This approach has been found to be useful (Hasan et al., 2019; Abdullah et al., 2018; Saghafian et al., 2014), although under-explored. Also, the monitoring of climate extremes, such as the possibility of droughts, have been few. For instance, currently return periods of dry spells has been carried out elsewhere by Caloiero et al. (2015); Sirangelo et al. (2019) over Southern Italy and Vicente-Serrano and Beguería-Portugués

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(2003) over North-eastern Spain. These dry and wet spells are crucial for understanding both agricultural and hydrological drought, but their frequency and return periods over a region are currently under-studied, especially the wet spells.

In Ghana, the Pra river catchment has gained increasing attention due to deforestation and illegal mining without land reclamation. These activities have significantly altered the eco-hydrology of the catchment in surface runoff (Awotwi et al., 2019), and coastal and urban flooding (Awotwi et al., 2017). Similarly, perennial urban and flash floods from short but high-intensity rainfall, in hand with weak drainage system network have been exacerbated as settlement rate increased to about 130% between 1986 and 2016 (Awotwi et al., 2018). Annual rainfall totals on the other hand, have been increasing since 1986 (Owusu and Waylen, 2009; Manzanas et al., 2014; Awotwi et al., 2017), which can also worsen the risk of flooding. Currently, in the face of hazards posed by rainfall extremes, flood and rainfall frequency analysis for flood forecasting at the catchment is absent. There are limited research-based outcomes on which early warning systems could be put in place to minimize the impact of rainfall variability on both lives and property. The Water Resource Commission of Ghana (Water Resource Commission, 2012) in 2012 undertook an Integrated Water Management Plan (IWRM) for the Pra catchment. The plan includes reducing the vulnerability of flooding at the catchment through the implementation of mitigation factors for alleviating the effects of floods and drought in the face of climate change. The commission (Water Resource Commission, 2012) hinted on the lack of flood management in development planning and laid down strategies such as rainwater harvesting systems, development of buffer zones along river banks and the restriction of settlement in flood prone areas of the catchment. There is the need to augment this policy action with reliable research outcomes for flood monitoring, assessment and management at the catchment.

In this work, for that matter, the Gumbel model was used to analyse the return periods of annual maxima floods, rainfall and wet and dry spells at the catchment. Specifically, the study (i) estimated the maximum rainfall, floods, wet and dry spells (ii) determined the return periods and probability of occurrence of these events at the Pra catchment. The remaining part of the paper is structured as follows: section 2 shows the study site under consideration, section 3 is the data and methods, section 4 is the results and discussions, with conclusions in section 5.

2. Study site description

The Pra river catchment (see Fig. 1) in Ghana lies between latitudes 5° N and 7°30′ N and longitudes 2°30′ W and 0°30′ W. It has a total area of approximately 23,200 km^2 (Water Resource Commission, 2012). Four major tributaries namely Birim, Oda, Anum and Offin, drain southwards into the main Pra river. The main Pra river is originates from the Kwahu Plateau and flows into the Gulf of Guinea at Shama in Ghana. At about latitude 6° N, the catchment can be divided into upper and lower Pra (Osei et al., 2021). At the middle of the catchment, the lake Bosomtwe can be found. The catchment is well-known for its legal and illegal gold mining especially in the Main Pra and Offin, with the Birim sub-catchment also known for its diamond extraction (Water Resource Commission, 2012). Most of the catchment towns are under rapid urbanisation and agricultural crop farming (Water Resource Commission, 2012).

Rainfall at the Pra catchment is controlled by the seasonal migration of the Inter-tropical Discontinuity (ITD) which dictates the West African Monsoon System (Amekudzi et al., 2015; Parker, 2017). From the ITD's movement, a bimodal rainy season is observed, a major between March and July, and minor from September to October. According to Osei et al. (2021), the annual rainfall varies between 1200 - 1700 mm and decreases at the extreme south and north of the catchment. In addition, annual temperature averages vary at 25 °C over highlands and forest regions and 27 °C over other areas of the catchment (Osei et al., 2021). The elevation from Fig. 1 is between 2 m and 830 m above mean sea level.

3. Data and methods

This section gives an overview of the datasets used to analyse the return periods and magnitudes of maxima rainfall, floods and consecutive dry and wet spells. Annual maxima rainfall and CDD and CWD were extracted from the CHIRPS gridded rainfall product. Annual maxima floods were estimated using the semi-distributed SWAT model after calibration and the model was run with fourteen in-situ climate station data within the Pra river catchment.

3.1. CHIRPS dataset

The Climate Hazards Group Infrared Precipitation combined with Station data (CHIRPS) is a highly-resolved gridded rainfall product, which combines global climatology with satellite estimates and in-situ observations (Peterson et al., 2013; Funk et al., 2015). The product can be obtained from daily to seasonal timescales and has a spatio-temporal resolution of 0.05°×0.05° and 1981 to present. In Ghana, the CHIRPS product has been validated and observed to have a good agreement with station rainfall data (Atiah et al., 2020). For this study, the version 2.0 (v2.0) of CHIRPS was obtained from 1981 to 2015 and used for the analysis in the spatial dynamics of maxima rainfall and return periods, and variations in CDD and CWD.

3.2. SWAT model setup and calibration

The Soil-Water-Assessment-Tool (SWAT) was set-up and calibrated on the daily timescale in order to obtain a long time-series of flow data which is not available at gauging stations at the Pra catchment. Data from these gauging stations are prone to long-term missing gaps which results in discontinuity inflow data for the Gumbel analysis. The SWAT model was developed by the United States Department of Agriculture to monitor the effect of agricultural land-use management practices on catchment hydrology (Arnold et al., 2012). The model was set-up on SWAT version 2012 (SWAT v2012) using QSWAT version 1.4 on the QGIS version 2.6.1 platform downloadable at http://swat.tamu.edu/software/. For the datasets to drive the model, digital elevation model (DEM) was obtained from SRTM version 3 (http://www.earthexplorer.usgs.gov) at a 3-Arc-Second Global resolution, soil map raster from FAOv3.6 (http://www.fao.org) at 1:5000000 m resolution and three land-use maps (1992, 2000 and 2015) obtained from European Space Agency Climate Change Initiative Land Cover version 1.6.1 (ESA CCI LC v1.6.1) (UCLouvain, 2017) at 300 m×300 m spatial resolutions. The model was also driven with climate data (daily rainfall and temperature) obtained from the Ghana Meteorological Agency for the period of 1970 to 2015 for the fourteen stations stated in Fig. 1. Daily stream-flow data were obtained from the Hydrological Services of Ghana for the Twifo-Praso gauging station along the Main Pra river for the period of 1970 to 2015. Data for the first five years (1970 to 1974) was used as model initialisation.

To ensure a satisfactory calibration with available observed stream-flow data for periods with no data gaps, the model was run for each land-use for a specified time-frame. The 1992 land-use map covers changes from 1975 to 1992 and it is a period when anthropogenic activities and conversion between various land-use classes were at a minimum (Awotwi et al., 2017, 2018). The 2000 land-use serves as a break-point for increasing anthropogenic activities between 1993 to 2000 (Awotwi et al., 2017, 2018). From 2000, there has been rapid conversion between land-uses with urbanisation increasing by 66.8% in 2004 and 130% by 2016 at the Pra catchment (Awotwi et al., 2017, 2018). The 2015 land-use map was therefore used for this land-use dynamics between 2001 to 2015 (Awotwi et al., 2017, 2018). In addition,

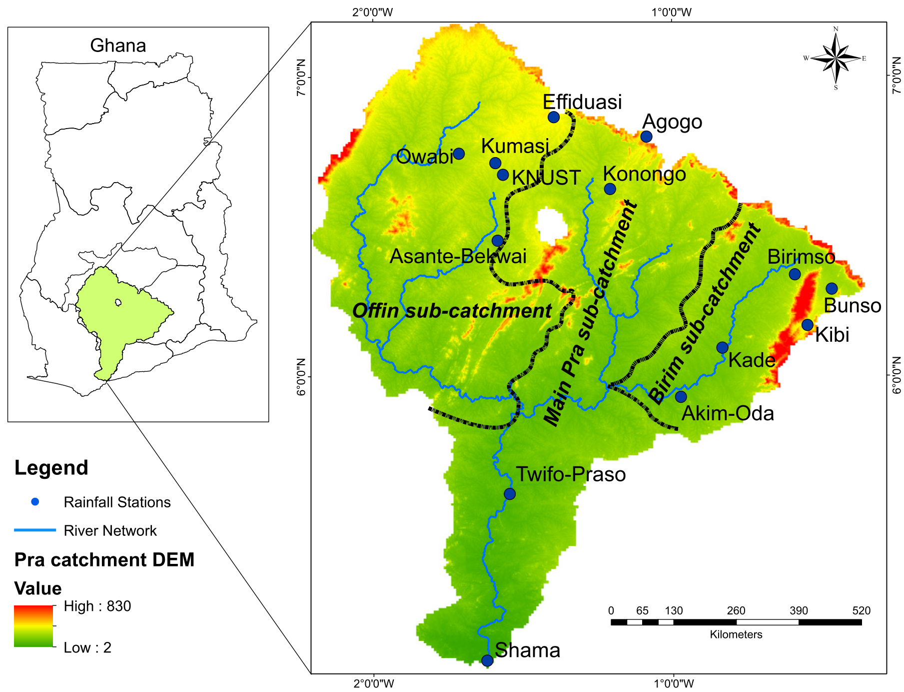

Fig. 1. The Pra river catchment of Ghana showing three sub-catchments namely Birim, Main Pra and Offin. The 6° N latitude is a boundary for separation of the catchment into upper and lower Pra.

the emergence of the mining land-use class in 2004 with a 3.55% of total land cover at the catchment and an increasing rate of 304% by 2016 (Awotwi et al., 2017, 2018) also served as basis for the employment of the 2015 land-use map. For the 1992 land-use map, the calibration period based on data availability was 1975 to 1978 (Fig. 2a), 1993 to 1994 for 2000 (Fig. 2b) and 2002 to 2004 for 2015 (Fig. 2c). It should be noted that, the climate data used to drive the model was likewise split into three, thus 1975 to 1992, 1993 to 2000 and 2001 to 2015 for the land-use phases 1992, 2000 and 2015. The calibration was carried out using the auto-calibration tool SWAT-CUP with the SUFI-2 algorithm. Table 1 shows the sensitive parameters that regulate streamflow generation at the catchment for each calibration phase. These parameters are related to the surface topography (curve number:CN2, surface runoff lag coefficient:SURLAG), groundwater (alpha factor for baseflow:ALPHA_BF, percolation fraction in deep aquifer:RCHRG_DP), physical processes within the catchment (soil evaporation compensation factor:ESCO) and the channel characteristics (Mannings 'n' coefficient:CH_N2, effective hydraulic conductivity in main alluvium channel:CH_K2). The temporal variability of these parameters after calibration ranged between 81 - 86 (CN2), 0.2 - 0.6 (ALPHA_BF), 0.06 - 0.2 (CH_N2), 0.17 - 0.3 (SURLAG), 28 - 54 (CH_K2), 0.83 (ESCO) and 0.04 (RCHRG_DP). Changes occurring for each of these parameters subsequently alters the streamflow dynamics at the Pra catchment on the daily timescale. Further information on the dynamics of these parameters can be obtained in Arnold et al. (2012). The calibrated stream-flow (see Fig. 2) shows a satisfactory correlation (R^2) and model efficiency (NS) as in Moriasi et al. (2007) between the simulated and observed streamflow for 1992/2000/2015. The p and r -factors which describe both model and parameter uncertainty is also observed to be satisfactory (Abbaspour, 2015) as the model enveloped about an average of 0.68 of the observed streamflow within an average width of 1.18.

After model calibration, the best optimal values obtained for the sensitive parameters (see Table 1) were re-written into the SWAT model and re-run on a daily timescale to obtain the continuous streamflow for the different sub-catchments of the Pra catchment. These model generated streamflow datasets, were used for the Gumbel extreme value analysis.

Table 1. Sensitive parameters for the three calibration phases.

1992	2000	2015
ALPHA_BF	CN2	ALPHA_BF
CN2	ALPHA_BF	CN2
CH_N2	CH_N2	CH_N2
SURLAG	SURLAG	SURLAG
CH_K2	ESCO	ESCO
	RCHRG_DP	
	CH_K2	

3.3. Statistical hypothesis and tools

3.3.1. Generalised extreme value theory

The core and tail of the annual maxima rainfall and flood data for each sub-catchment were tested to conform to the Generalised Extreme Value Theory (GEV) with a null hypothesis that the data does not follow the GEV for Gumbel and the alternate hypothesis of the data following the GEV for Gumbel distribution. The R software (Team et al., 2013) was used along with packages gumbel (Caillat et al., 2018) and extRemes (Gilleland and Gilleland, 2020) for these analysis. The GEV distribution is shown in Equation (1).

$$f(Q|\mu,\sigma,\epsilon) = \frac{1}{\sigma}\left[1+\epsilon\frac{Q-\mu}{\sigma}\right]^{\frac{-1}{\epsilon-1}} \exp-\left[1+\epsilon\frac{Q-\mu}{\sigma}\right]^{\frac{-1}{\epsilon}} \quad (1)$$

where Q is the annual maxima rainfall or flood, μ is the location parameter, σ is the scale parameter and ϵ is the shape parameter. The Maximum Likelihood Estimation method was used to obtain the location, scale and shape parameters. For the test of the core, the maxima rainfall and flood were observed to follow the Gumbel distribution with significant p-values less than 0.05 based on the Kolmogorov-Smirnov goodness-of-fit test. The location and scale parameters obtained for maxima rainfall and flood can be observed in Table 2. The shape parameter governs the tail of the distribution of GEV, such that values of approximately zero is assumed to follow the Gumbel distribution (Ragulina and Reitan, 2017; Embrechts et al., 2013), whereas negative and positive values represent the Weibull and Frichet distributions respectively. (Embrechts et al., 2013) In Table 2, ϵ was observed to be closer

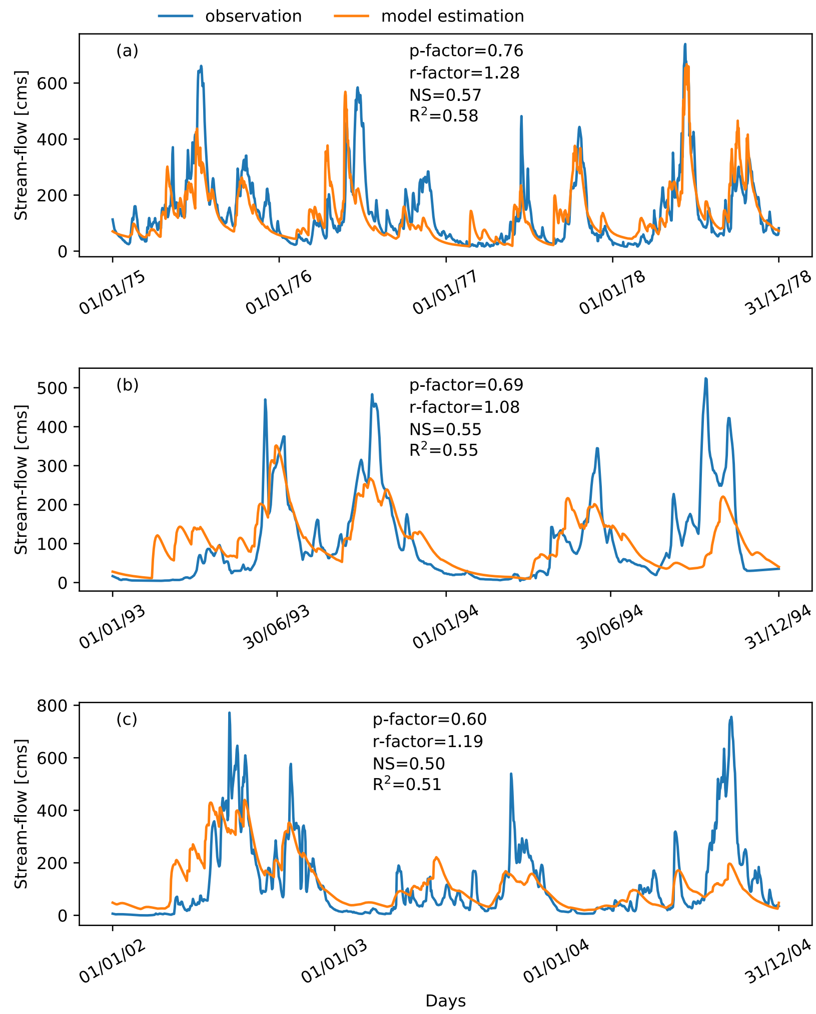

Fig. 2. Daily calibrated stream-flow for the three land use phases. (a) 1992 (1975 to 1978), (b) 2000 (1993 to 1994), (c) 2015 (2002 to 2004). The streamflow is measured in cumecs (cms).

Table 2. Scale, location and shape parameters of maxima rainfall and floods at the three sub-catchments.

Sub-catchment	scale parameter (σ)	location parameter (μ)	shape parameter (ϵ)
Maxima rainfall			
Birim	8.25	41.56	−0.19
Offin	7.22	48.39	−0.17
Main Pra	7.87	41.49	0.08
Maxima flood			
Birim	564.37	1369.7	0.10
Offin	692.36	1856.7	0.07
Main Pra	988.46	3663.6	0.04

to zero, which indicated that the data indeed followed the Gumbel distribution. Furthermore, the tail of the dataset are found to be positive (right) skewed as observed in Fig. 3, which also supports the GEV alternate hypothesis.

3.3.2. Gumbel method

The Gumbel extreme value distribution (Gumbel, 1941) is a statistical method that has been applied for the estimation of return period of floods and maxima rainfall. The Gumbel distribution is such that, the probability of occurrence of maxima flood/rainfall ≤ Q is given by:

$$P = 1 - e^{-e^{-y}} \tag{2}$$

and the reduced variate y is given by:

$$y = -0.834 - 2.303 \log \log \frac{T}{T-1} \tag{3}$$

y has a linear relationship with the variate Q, and can be related as:

$$y = \sigma_n \left(\frac{Q - \bar{Q}}{\sigma} \right) + \bar{y}_n \tag{4}$$

where the reduced standard deviation, σ_n and the reduced mean, $\bar{y}_n$, are variables which are functions of the number of samples of flow data and can be obtained from Gumbel probability tables (Selaman et al., 2007). Equation (2) can be rewritten as:

$$Q_T = \bar{Q} + K\sigma \tag{5}$$

where Q_T is the annual flood maxima which has a recurrence interval (return period) T, $\bar{Q}$ which is the mean of the maxima flows and K is the frequency factor given as: $\frac{y-\bar{y}_n}{\sigma_n}$. Equations (2) to (5) were obtained from Raghunath (2006), from which further inferences can be made.

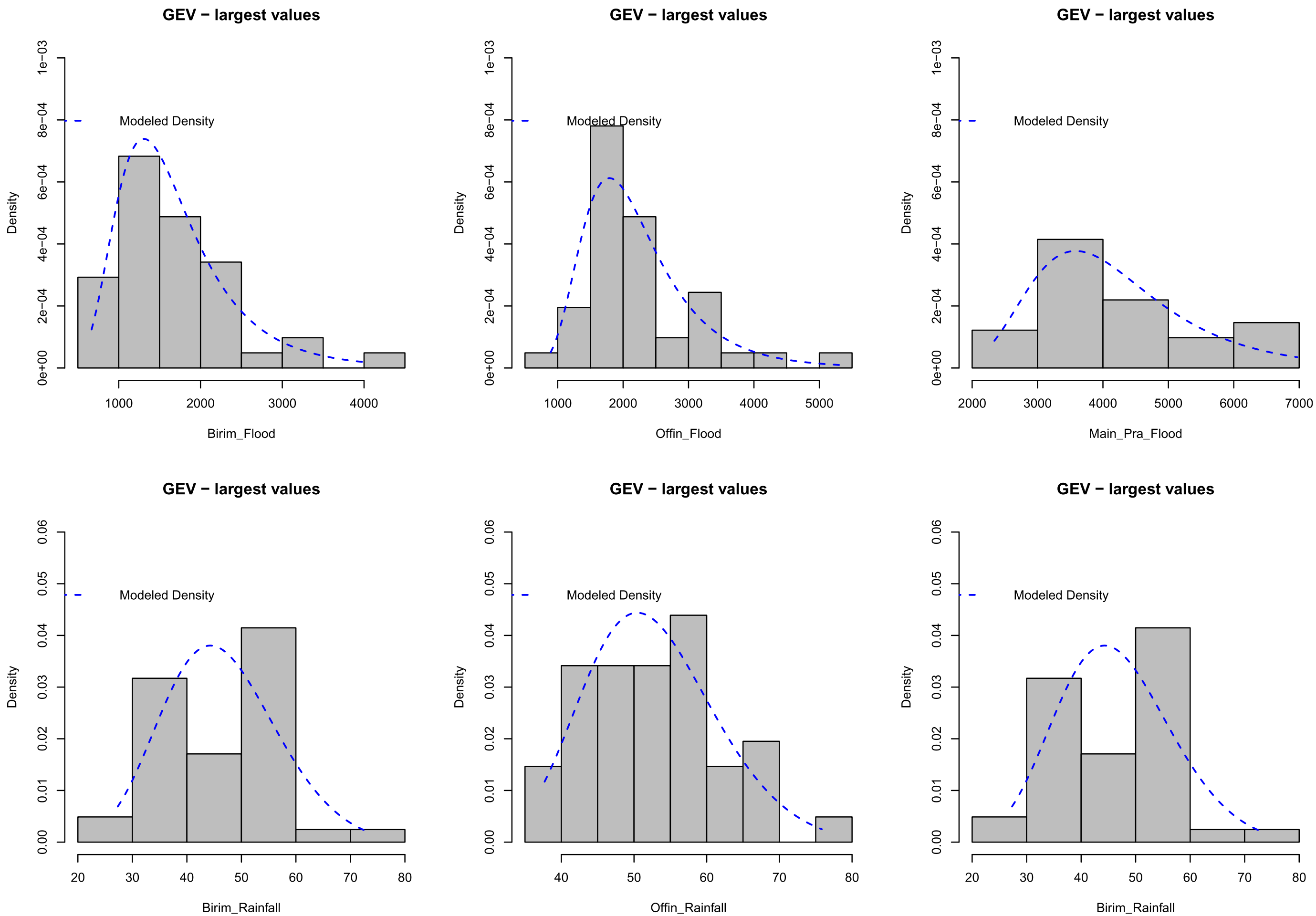

Fig. 3. Positive skewed distribution of the GEV for the maxima rainfall and simulated maxima floods at the sub-catchments.

Table 3. Reduced variate (y) and frequency factor (K) for the different return periods of simulated flood maxima from the SWAT model and CHIRPS rainfall estimates at the catchment.

T_p	y	K
5	1.49	0.85
10	2.25	1.51
25	3.19	2.36
50	3.39	2.98
75	4.31	3.34
100	4.60	3.59

There are two possible solutions for the Gumbel method. The first is a solution to determine the return period T based on Equation (3) of a given annual flow maxima (Q_T) and its probability of occurrence P (Equation (2)) and the second is a solution to determine the annual flow maxima (Q_T) based on Equation (5) for a given return period T. The first solution was applied to the maxima flood data obtained from the SWAT model while for maxima rainfall, consecutive dry days (CDD) and consecutive wet days (CWD), the second solution only was used.

Table 3 shows the reduced variate (y) and frequency factor (K) for different return periods of maxima floods and rainfall for the Pra catchment. These values hold for all the three sub-catchments. The reduced mean ($\bar{y}_n$) and reduced standard deviation (σ_n) for maxima flow were from Gumbel distribution table (see (Raghunath, 2006)) of 0.5442 and 1.1436 respectively.

4. Results and discussions

This section entails the results obtained after subjecting the hydro-meteorological variables under consideration to the Gumbel's distribution. The climatology of the variables are discussed along with their expected magnitude for different return periods.

4.1. Maxima rainfall dynamics

The variability of the mean and standard deviation of maxima rainfall at the Pra catchment is shown in Fig. 4. It should be noted that, Fig. 4a indicates the spatial distribution of the 35 year mean of maxima rainfall and does not necessarily indicate higher annual rainfall amounts for same areas as observed in the rainfall climatology in Osei et al. (2021). The climatology of the maxima rainfall ranges between 35 mm to 95 mm with corresponding standard deviation of 6 mm to 30 mm respectively per year. The reduced mean ($\bar{y}_n$) and reduced standard deviation (σ_n) for maxima rainfall were found to be 0.5403 and 1.1285 respectively. In addition, the respective reduced variate (y) and frequency factor (K) for the maxima rainfall can be found in Table 3. From Fig. 4a, the highest rainfall maxima is observed at the south of the catchment with a value of about 90 mm at the immediate outlet at Shama, where the Pra river flows into the Gulf of Guinea. The upper Pra catchment consisting of the Birim, Offin and upper Main Pra sub-catchments, and characterised by mountainous ranges (Birim) with forested and agricultural land-uses (Birim and Main Pra) were observed to have low to moderate amounts in maxima rainfall (35 - 60 mm). The central part of the catchment where Lake Bosomtwe is located,

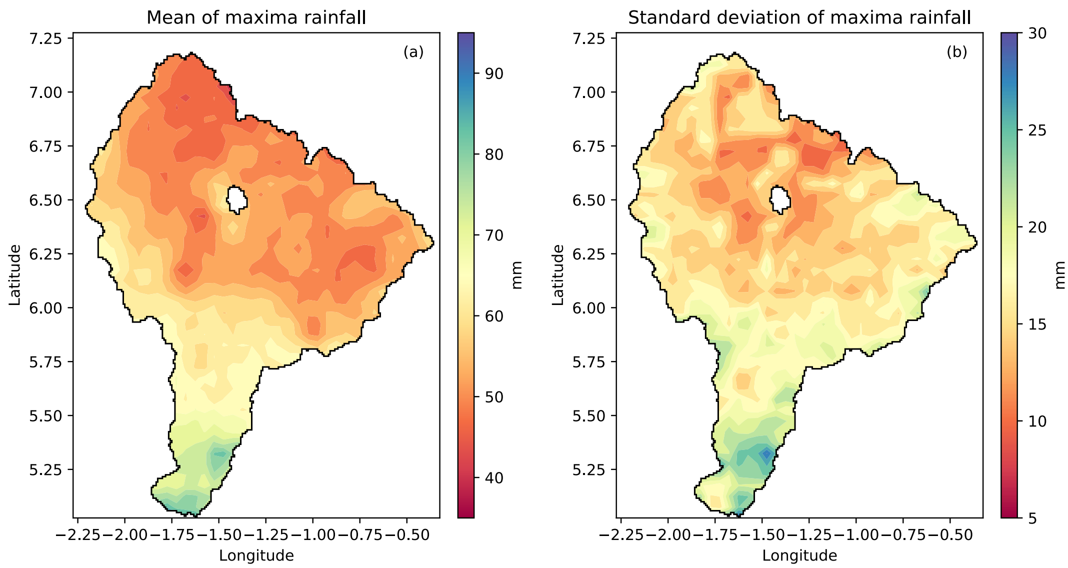

Fig. 4. (a) Mean and (b) standard deviation of maxima rainfall over the period of 1981 to 2015 from the CHIRPS dataset.

was found to have maxima rainfall between 60 - 65 mm. The low maxima rainfall values (35 - 50 mm) within the northern part of the catchment may be due to its moderate to high urbanised land-use characteristics (Awotwi et al., 2018). The spatial variation of the standard deviation (Fig. 4b) is observed to be analogous to the mean maxima rainfall (Fig. 4a). That is, higher standard deviations were observed for areas with high mean maxima rainfall and vice versa.

Fig. 5 shows the magnitude of maxima rainfall for six predicted return periods (5, 10, 25, 50, 75 and 100) at the Pra catchment. An increasing amount in maxima rainfall is expected at the river catchment. Generally, this is expected to favour the south of the catchment towards the coast than inland areas, especially at the centre of the Pra catchment. The total amounts from 5 to 100 years range between 40 mm to 190 mm. A peculiar observation was the emergence of a new maxima for all return periods at the south of the catchment as also observed in the climatology (Fig. 4a). In the same figure, the mean of the baseline (1981 to 2015) attained a maximum of 95 mm. The 5 year return period (Fig. 5a) showed an increase to about 120 mm as compared to the baseline, and also centred at the southern location observed for the baseline (Fig. 4a). The 10 (Fig. 5b) and 25 (Fig. 5c) year period showed a maxima to occur within 120 - 160 mm, with lower variation further inland.

In 50 years (Fig. 5d), the magnitude of rainfall for the upper Pra increased to about 120 mm. Meanwhile, the lower Pra lies between 120 mm to approximately 180 mm. The nucleus of 180 mm at the south is expected to further expand from the 75 (Fig. 5e) to 100 (Fig. 5f) year return periods (Fig. 5), while the 90 to 110 mm isopleths located inland gradually disappears to be replaced by 120 mm isopleths. In the 75 to 100 year period, a maxima of 180 to 190 mm, surrounded by 160 to 170 mm isopleths appear at Shama. The continual emergence of local maxima at Shama for the return periods raises much concern as the elevation is generally low with an average of 70 m above mean sea level. The delicate coastline at Shama has over the years made the location susceptible to perennial flooding from riverine floods to sea level rise. A concurrent increase in maxima rainfall amount is bound to exacerbate the flooding events. It has been reported that there is an ongoing relocation of settlements along the outlet of the catchment due to an annual increase in inundations from rainfall (Center, 2013). The sea defense systems at the outlet therefore needs to be strengthened to prevent the havoc of the expected volumes in maxima rainfall. Although the maximum rainfall amounts show an increase under the various return periods, anthropogenic activities at the catchment is likely to induce some changes in the magnitude. For instance, convective rainfall activities are likely to decline as deforestation and settlement increase at the catchment to accommodate population explosion. This would result in a lower magnitude with a likely short but intense rainfall maxima in subsequent years. Lastly, the transitions of maxima rainfall amounts from baseline to 5 years, 5 - 10, 10 - 25, 25 - 50, 50 - 75 and 75 - 100 years had decreasing rates of 26%, 17%, 14%, 13%, 0% and 5% respectively. The no change in percentage for the 50 - 75 year is due to the expansion of the 180 mm isopleth in the 50 to 75 years.

4.2. Consecutive dry and wet days (CDD and CWD) dynamics

Fig. 6 shows the 35 year mean consecutive dry days (CDD) and consecutive wet days (CWD), as well as their standard deviations for the Pra catchment. CDD (Fig. 6a) is observed to increase to the south of the catchment with the maximum spell length ranging between 25 to 65 days and a maxima of 60 to 65 days further south. The mid-catchment is characterised by a higher percentage of the total CDD for the entire catchment with lengths of approximately 25 to 40 days. In addition, this covers the major part of the Offin and Birim sub-catchments. Furthermore, the northernmost areas of the catchment has the lowest variability in the number of CDDs ranging between 25 to 30. The maximum dry spell duration basically arise from the presence of the dry monsoon over the region and hardly from events during the wet monsoon over West Africa. The consecutive wet days shown in Fig. 6b on the other hand reveals less linear variations at the catchment. The duration is also found to be low as compared to the CDD. Higher CWD duration (between 10 to 12 days) is found at the Birim sub-catchment. Meanwhile, a larger percentage of maximum wet spell durations of 8 to 10 days can be found at Offin sub-catchment. The minima of CWD (6 to 7 days) is found at the south of the catchment, as opposed to the CDD maxima (Fig. 6a) which is found at the north of the catchment. It can also be observed that a vast majority of the catchment is engulfed with CWDs between 8 to 10 days. The corresponding standard deviations can be observed in Fig. 6c and Fig. 6d respectively. A positive correlation can be observed between the mean and standard deviations of CDD (Figs. 6a and b), with high averages linked to higher standard deviations. These deviations for the dry spells (Fig. 6b) range between 5 to 30 days and 1.5 to 4.5 days for the wet spells (Fig. 6c). The lowest deviations of CDD (Fig. 6b) is found at north of the Pra catchment. The standard deviation of CWD (Fig. 6d) showed various degree of variability within the entire catchment. The eastern (which also contains the Birim sub-catchment) is characterised by deviations of 2.5 to 4.5 days. The central part of the catchment around the lake Bosomtwe also has a

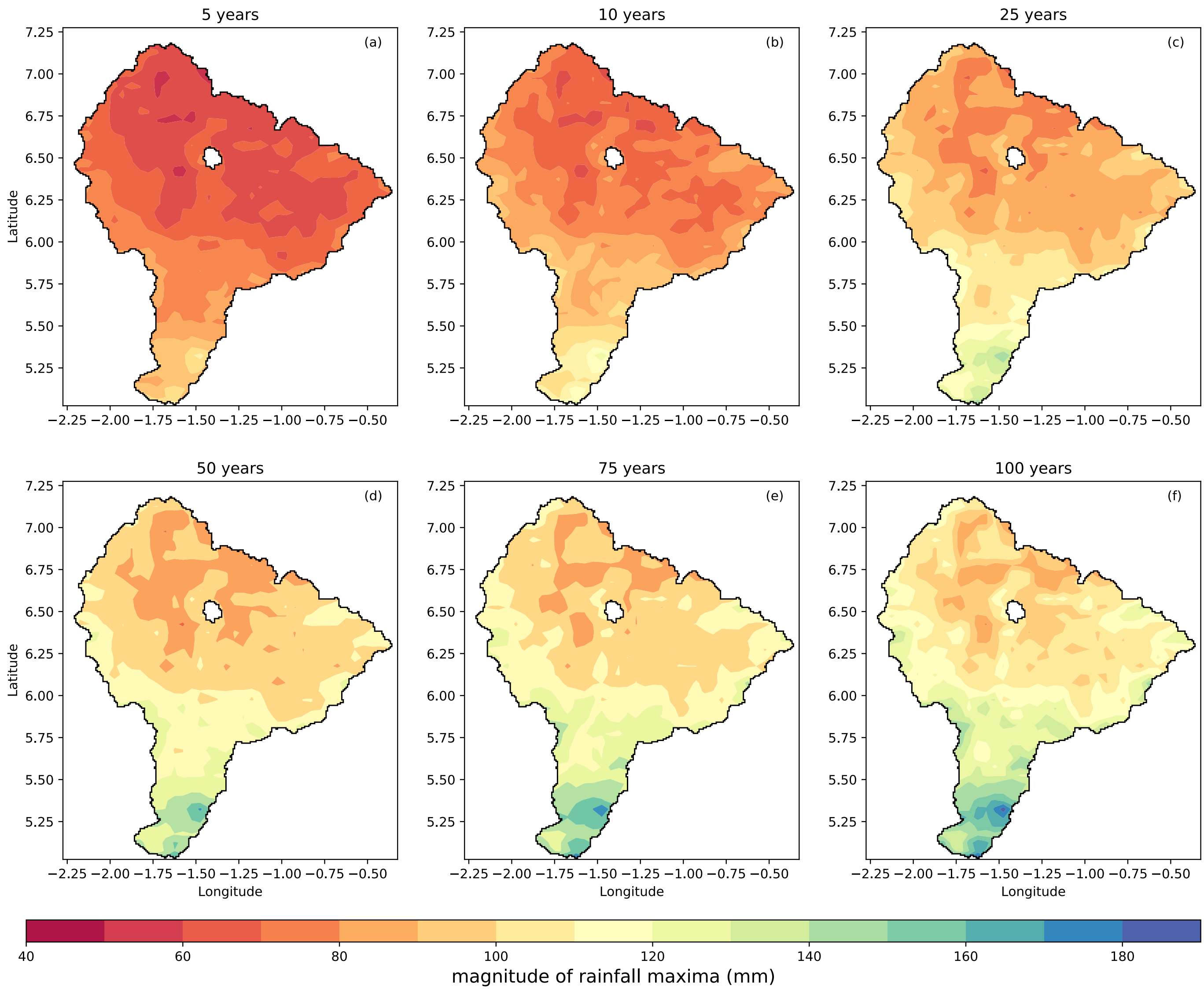

Fig. 5. Expected magnitude of rainfall for return periods, (a) 5, (b) 10, (c) 25, (d) 50, (e) 75 and (f) 100 years from the baseline period (1981 - 2015). The return period is calculated in accordance with Gumbel solution 2.

higher deviation analogous to the east. On the other hand, the south has the least of CWD deviations ranging from 1.5 to about 3 days. Lastly, the Offin sub-catchment has deviations pre-dominantly between 2 to 3 days from the mean.

4.2.1. CDD and CWD for various return periods

Figs. 7 and 8 show the variation of consecutive dry days (CDD) and consecutive wet days (CWD) for different return periods at the Pra catchment. Magnitude of CDD is expected to be higher than CWD with a north-south increase in CDD (Figs. 7 and 8). The maxima observed in Fig. 6a for the average CDD of approximately 65 days at the south is increased to about 75 days (Fig. 7a) for the 5 year return period. The 10 year (Fig. 7b) showed variation in only minima and maxima CDD as compared to the 5 year period. A northward withdrawal of the 5 year minima of 35 to 45 days and the initiation of a maxima of 95 to 105 days at the south (Shama) is observed for the 10 year period. A new local maxima still at Shama is between 125 to 135 days in the 25 year (Fig. 7c) return period. The increasing maximum dry days becomes prominent from the 50 year (Fig. 7d) return period. The 50 year (Fig. 7d) return period at this stage has a lower limit of 45 to 55 days at upper Pra which gradually retreat northward as compared to the 10 and 25 year period. On the other hand, for the 75 year (Fig. 7e) return period, this lower limit is observed to have disappeared except for few places in the Offin sub-catchment. The magnitude of the inland CDD for the 75 years is expected to range from 45 to about 95 days. For the 100 year (Fig. 7f) return period, a difference in CDD is observed at the south which shows a new increment to 175 days and an expansion of the 165 to 175 day isopleths observed at the south (Shama) during the 75 year period. However, the north of the catchment is expected to experience CDDs of magnitude 55 to 85 days while the mid-catchment is expected to range between 80 to 95 days.

The CWDs for the stipulated return periods are shown in Fig. 8. High wet spell frequencies are expected to occur at the centre of the catchments especially at the Lake Bosomtwe. Besides, the variation of the CWD is topography dependent, with higher CWD associated with higher elevations. It is observed that, relative to the mean of the baseline period (see Fig. 6c) which obtained highest maxima to be around 11 days, the 5 year (Fig. 8a) period is expected to observe maxima of atleast 10 to 14 days in durations. These maxima have a large coverage at the Birim sub-catchment (north-east at the Pra catchment), with additional areas within the central Pra catchment. South of the catchment which was characterised by 6 - 7 days is expected to increase to about 8 - 10 days. In addition, the 10 years (Fig. 8b) shows limits of 6 to 20 days in the CWD. A total catchment coverage except at the im-

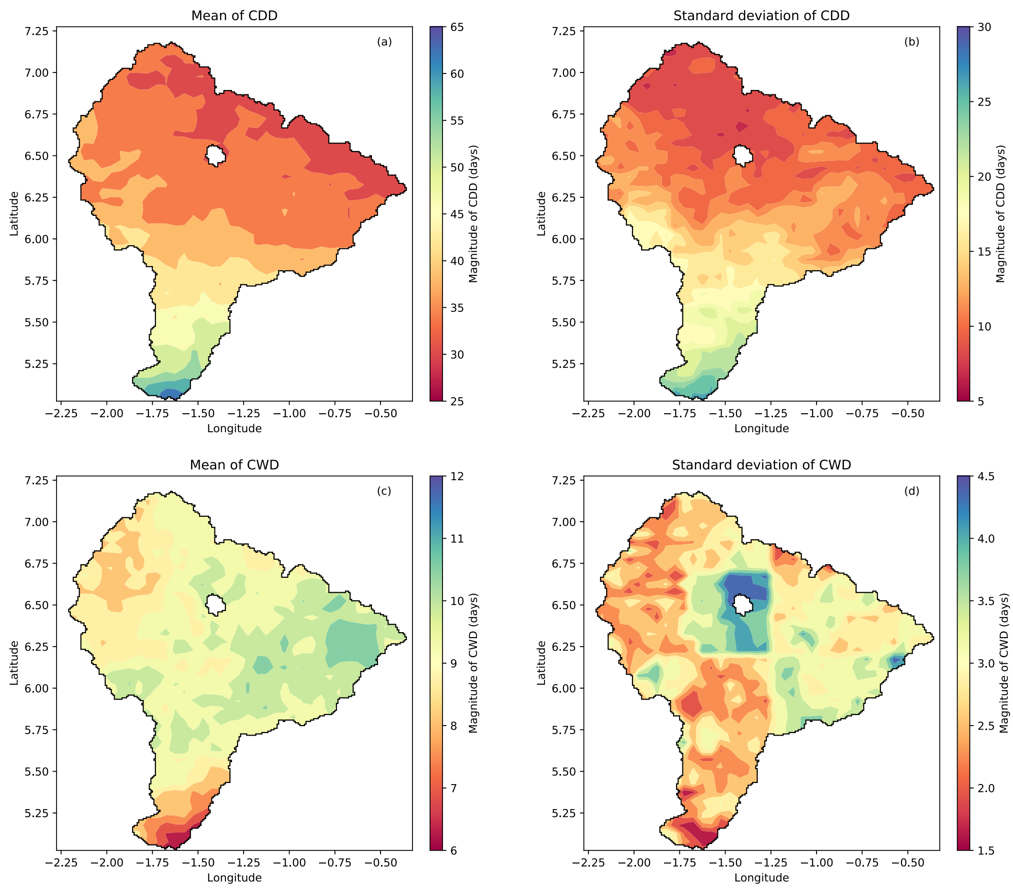

Fig. 6. Mean and standard deviation for consecutive dry days (CDD) and consecutive wet days (CWD) from 1981 to 2015 obtained from CHIRPS dataset analysis.

mediate south shows an extension of the 12 to 20 days in the 25 year (Fig. 8c) period and the appearance of the 20 to 22 days at the central and localised north-east portion of the catchment. For the 50 year return period (Fig. 8d), maxima spell frequency are expected to range between 16 to 24 days with the lowest duration of 10 to 12 days at the south. Nevertheless, only few locations are expected to retain the 12 to 14 days which were prominent in the 25 year. The 75 (Fig. 8e) and 100 year periods (Fig. 8f) revealed new magnitudes in the duration of wet spells which extended from 10 to 28 and 12 to 28 days respectively. The southern minima of 10 to 12 days diminish (75 years) and disappears in the 100 years. This has been subsequently replaced by the 12 to 14 days. Hotspots for maxima in wet spells is again expected to be close to the Lake Bosomtwe and the localised Birim sub-catchment, with 30 days observed for the latter catchment in 100 years. The second maxima that appears in the vicinity of the Lake Bosomtwe may be due to the local effect of the water body on the rainfall pattern at the area. Furthermore, the Birim sub-catchment which also has high frequency CWD (20 to 30 days) may be under the influence of the topography and the forested and agricultural land-uses.

Comparatively, it can be observed that the nucleus of high CDDs (Figs. 6a and 7) at the south of the catchment is also characterised by high maxima rainfall (Figs. 4a and 5) and low CWD (Figs. 6c and 8). This implies that the maxima rainfall observed in Fig. 4a for these locations, as well as that found for the various rainfall return periods (Fig. 5) may result from shorter duration wet spells such as the 2 - 3 and 4 - 5 day spells and not necessarily from the maximum consecutive wet spells in Figs. 6c and 8. Furthermore, it can be observed that the locations of high CDDs are associated with relatively low rainfall climatology observed by Osei et al. (2021), resulting in a higher risk of drought conditions if the current trend due to deforestation for illegal mining activities and timber logging for constructional works in urbanisation persists. The nucleus of high dry spells and its link with annual rainfall amounts has also been observed at Catalonia, Spain (Lana et al., 2008). According to Awotwi et al. (2018), there is a high probability of a northward expansion of urbanisation at the upper Pra catchment at the expense of cropland and open forest by 2025. In addition, increased alluvial mining at the south and expansion of croplands at the expense of closed and open forest at the middle of the catchment is also expected by 2025 (Awotwi et al., 2018). These alterations in the land-use dynamics at the catchment, especially of closed and open forests to croplands enhance the chances of increasing CDDs at the catchment. The agricultural sector is likely to be most affected by this progressive increase in the CDD through the various return periods, as the agricultural system is purely rain-fed and the main source of livelihood for about 63% of the inhabitants at the catchment (Water Resource Commission, 2012). Drought conditions are likely to develop in these areas in the future with crop and livestock water demands increasing concurrently. Therefore, the re-enforcement of bore-hole utilisation and rainwater harvesting policies that have been laid down by the water resource commission of Ghana (Water Resource Commission, 2012) for irrigation purposes has to be of high priority to water management at the catchment. The topography of a catchment is known to play a crucial role in regulating dry spell durations. Higher reliefs significantly lowers the probabilities of long dry spells of a region (Caloiero et al., 2015). This can also be found in further inland regions of the Pra catchment where the elevation is high (see Fig. 1) and a subsequent reduction in consecutive dry spells (Figs. 6a and 7). In addition to the terrain, the land-use of the inland region is also dominated by deciduous and semi-deciduous forests and agricultural land cover, which also influences the dry spell durations. The increment of consecutive dry spells for the various return periods (Fig. 7) can also result from anthropogenic activities such as the already stated deforestation at the catchment.

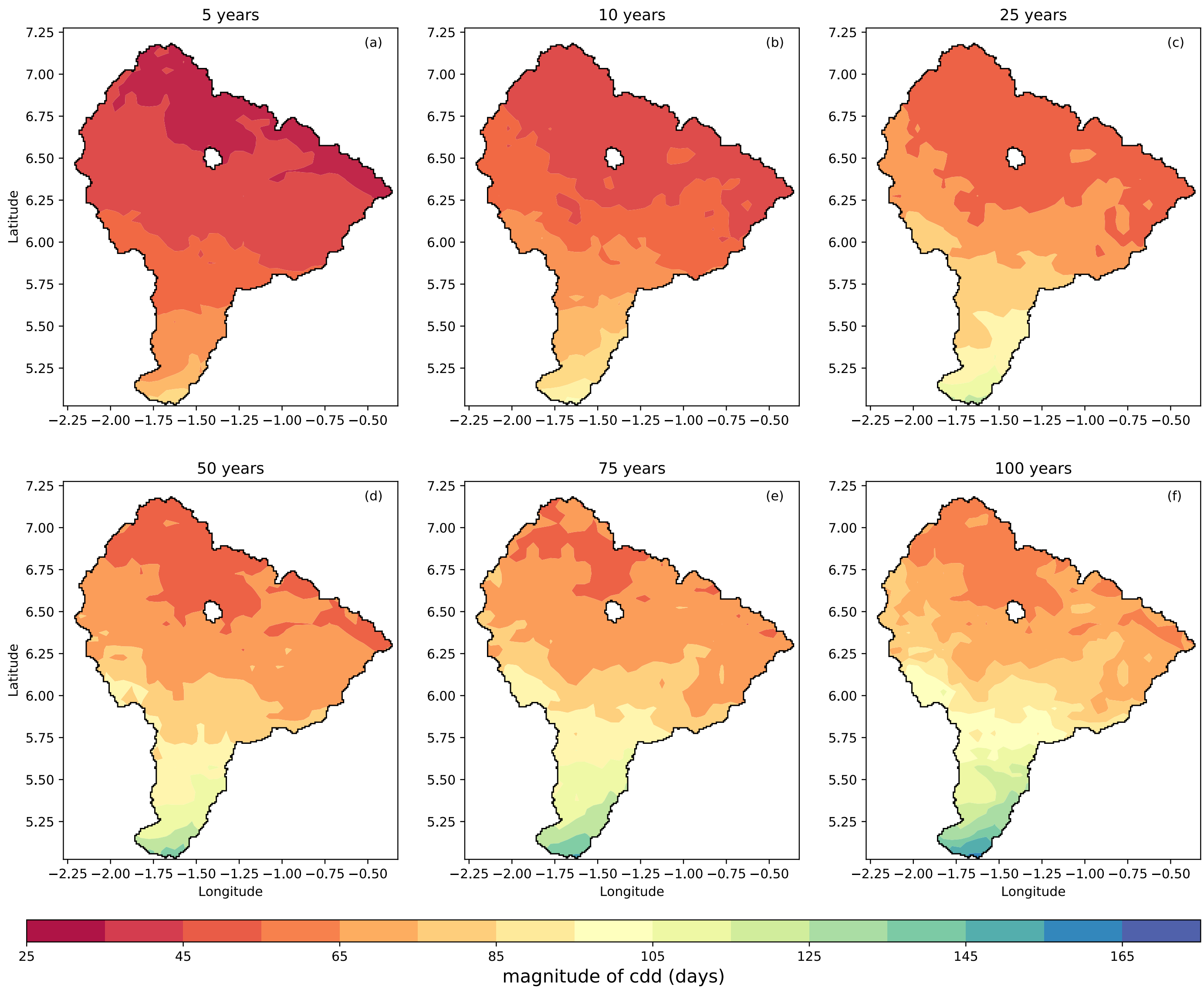

Fig. 7. Expected magnitude of consecutive dry days (CDD) for return periods, (a) 5, (b) 10, (c) 25, (d) 50, (e) 75 and (f) 100 years from the baseline period (1981 - 2015). The return period is calculated in accordance with Gumbel solution 2.

4.3. Maxima flood estimated from the SWAT model

Fig. 9 shows the annual maxima flood estimated from the calibrated SWAT model for the three sub-catchments (Birim, Offin and Main Pra). The mean/standard deviation of maxima flow was 1695.46/723.83 cms (Birim), 2601.70/1049.70 cms (Offin) and 4234.14/1267.74 cms (Main Pra). The Main Pra sub-catchment is observed to have the highest maxima followed by the Offin and least at the Birim sub-catchment. An overall increasing trend is found in the maxima flood time-series at the three sub-catchments with the highest magnitude at Birim (8.31 cms/year) as compared to Offin (6.38 cms/year) and Main Pra (5.97 cms/year). The sub-catchments observed a decline in maxima floods between 1985 to 2000 with the increase in the last decade probably attributable to the recovery of rainfall regimes over Ghana (Owusu and Waylen, 2012). This may also result from the gradual increase in urbanisation with the break-point year observed from the early 2000s (Awotwi et al., 2018). However, periodic maximum floods was found in the year 1993 for Birim and Main Pra where the amount reached about 3070 cms and 6020 cms respectively (Fig. 9). Besides, maxima floods at Birim are almost one-half the flood amounts that exist at the Main Pra sub-catchment. Furthermore, the lowest maxima flows occurred in different years at the sub-catchments. The maximum/minimum found at the sub-catchments include: 4010cms/668cms for Birim in 2002 and 1999, 5350cms/892cms at Offin in 2008 and 1990 and 6970cms/2340cms at Main Pra for 1976 and 1990.

Although Birim sub-catchment (areal mean of 3804.16 km^2) is characterised by mountainous ranges and highlands (which ultimately should result in increased runoff), as compared to the other sub-catchments, its least annual maxima floods may be attributed to the existence of agricultural activities (farming) and dense evergreen forest covers. Agricultural activities comprising of both row crops and land generic crops as at 2015 account for a major percentage of about 84.43% (3211.48 km^2) of the sub-catchment as evergreen, semi-deciduous and mixed forests accrue the next highest coverage of 13.76% (523.36 km^2). These land-uses increase the concentration time of surface runoff permitting a greater amount of water to percolate into the soil and a subsequent reduction in maxima flows. The topography is also obtained to be about 92 m (minimum) to 842 m (maximum for both sub-catchment and entire Pra catchment) and a mean elevation and standard deviation of 210.94 m and 117.62 m respectively. The maximum records of maxima floods at the Main Pra sub-catchment is mainly due to the presence of the flow path of the Pra river in which

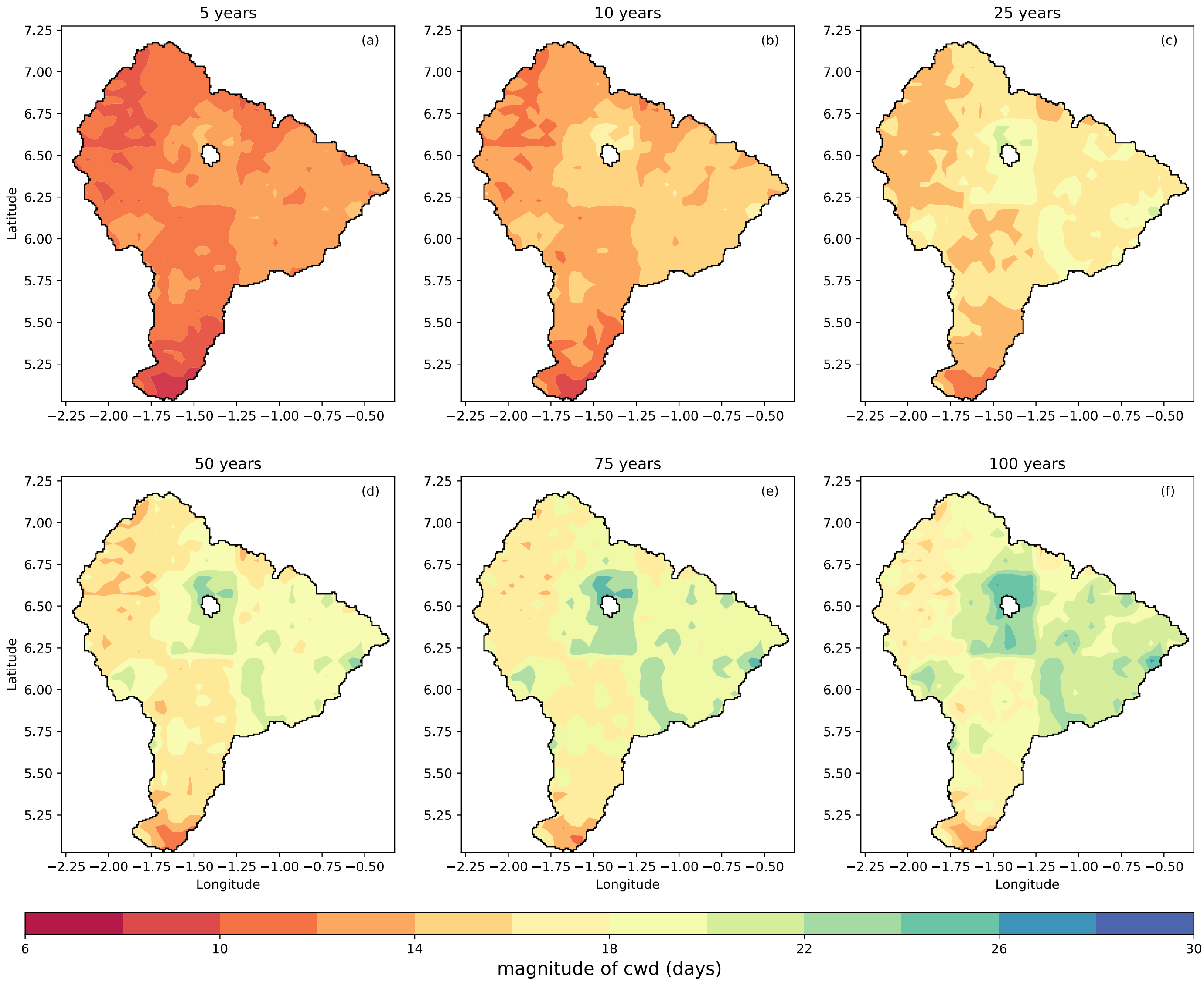

Fig. 8. Expected magnitude of consecutive wet days (CWD) for return periods, (a) 5, (b) 10, (c) 25, (d) 50, (e) 75 and (f) 100 years from the baseline period (1981 - 2015). The return period is calculated in accordance with Gumbel solution 2.

its major tributaries, rivers Offin and Birim, as well as minor tributaries such as rivers Oda and Anum among others converge. This increases the volume of water that leaves the basin outlet (at Shama) daily and hence a corresponding increase in the maxima flood amounts. The Offin sub-catchment which is larger than the Birim sub-catchment is observed to produce moderate maxima floods.

4.4. Flood frequency curve

Fig. 10 shows the flood frequency curve which indicates the return period for the baseline annual flood maxima with the Gumbel method. The return periods for two-thirds of flood of magnitudes, thus $\leq$ 3000 cms for Birim, 4000 cms Offin and 6500 cms for Main Pra, were found to be less than 20 years. This implies that, for floods of such magnitude at the sub-catchments there is a 5% chance of occurrence/exceedance within any year in 20 years. The highest estimated return year for the maximum flood amount at Birim and Offin is 108 and 95 years respectively, with a probability of occurrence $\leq$ 1%. But, according to England et al. (2019), such low exceedance probability floods can accumulate over time, such that over a 25 to 50 year period, its magnitude can become substantial. Therefore, a low exceedance probability cannot be slightly overlooked in flood risk analysis at the catchment. The return period at Main Pra (Fig. 10) was obtained to be lower (29 years) for the upper limit flood which may imply the higher concentration of water from the entire catchment resulting in a higher probability of the maximum flood occurring within three decades. Lower magnitude floods of 1 to 2 year return periods should be of critical importance, since they have about 50% to 100% chance of occurrence within any given year.

With the ongoing increase in the frequency of coastal, river and flash floods due to changing rainfall patterns, urbanisation and other anthropogenic activities such as the popular illegal mining at the Pra catchment, it follows that the return of these floods, as well as a likely increase in future years at the catchment would pose dire problems for both settlements and socio-economic and agricultural activities. For instance, the low-lying coastal area of Shama, which serves as the outlet for the Pra river, is already plagued with perennial river and coastal flooding. For 2, 6 and 10 feet rise in sea level, the area of Shama is expected to have a coastal flooding with coverage of 2.5 km^2, 4.7 km^2 and 6.2 km^2 and an affected population of 1394, 2510 and 3341 respectively (Adortse, 2019). These coastal inundations would be exacerbated by the increases in the number of higher rainfall maxima (Fig. 5) and a subsequent disruption of fishery activities and destruction of infrastructure at affected communities. The Offin sub-catchment currently is witnessing rapid urbanisation with a higher concentration at the Ku-

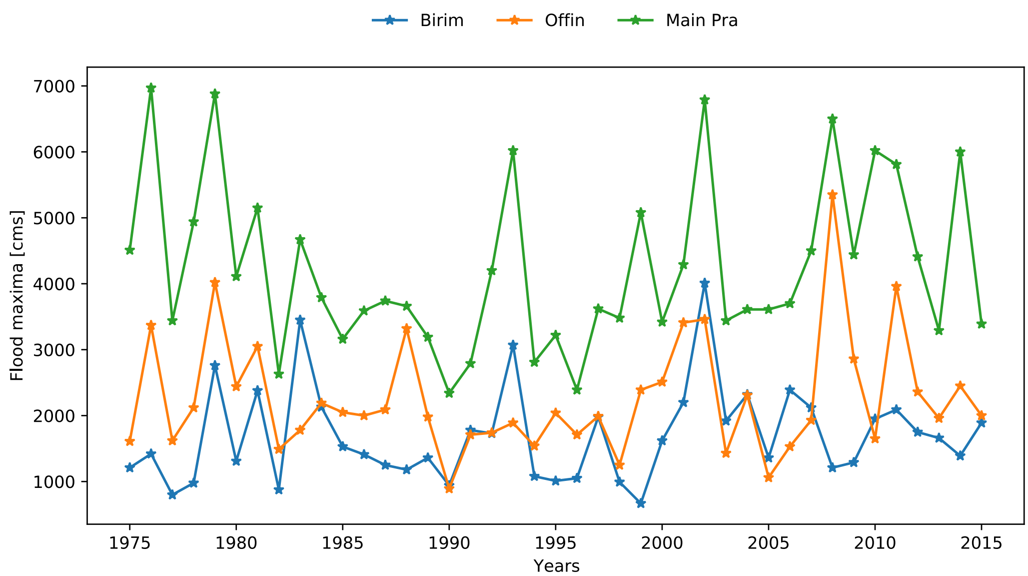

Fig. 9. Annual maxima distribution of flood volumes from 1975 to 2015 for the three main sub-catchments of the Pra catchment. The flood volumes were extracted from the calibrated SWAT model.

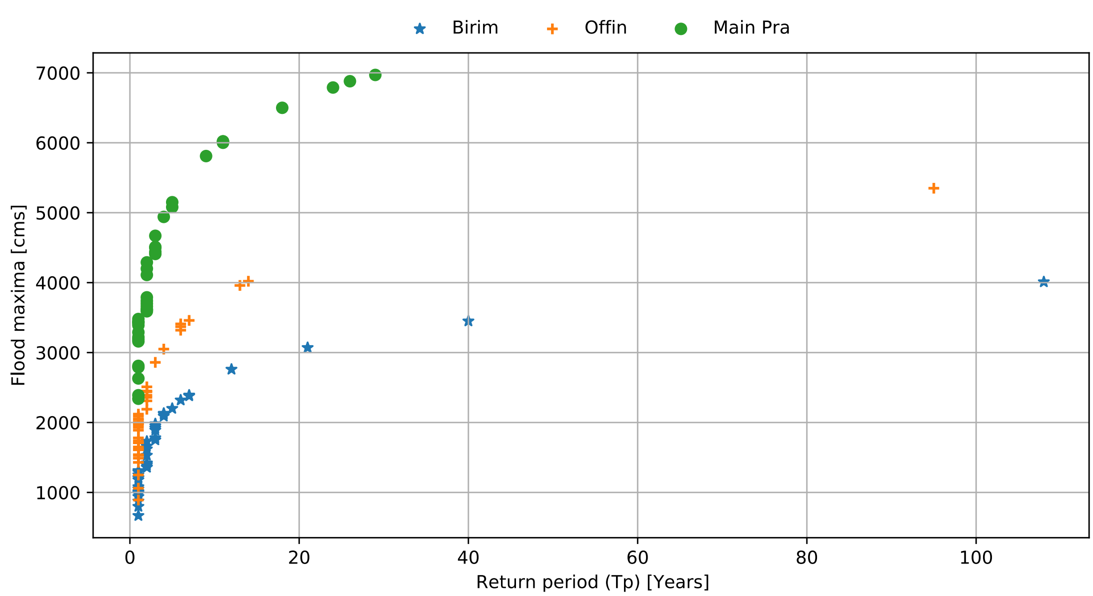

Fig. 10. Flood frequency curve for Gumbel distribution. This gives the return period of floods based on the baseline floods and falls under the approach to Gumbel solution 1.

masi metropolis. Seasonal flash and river flooding are a norm which has resulted in loss of lives and damages to properties. These floods are mainly due to poor drainage and sewage systems, as well as sanitation issues (Asumadu-Sarkodie et al., 2015) in the urban areas. With the expected increase in rainfall and flood volumes (see Figs. 5), the damages to lives and properties are also expected to be high in the absence of proper drainage and flood defense systems. At the Birim catchment, flood magnitudes are low, as observed from the flood frequency curve in Fig. 10, but there is still the need to put in place adequate adaptation and mitigation measures for expected flood recurrence at the sub-catchment. The building of smaller dams and reservoir systems, can minimise the impact of these floods at the entire Pra catchment.

5. Conclusions

The Pra River catchment in Ghana is affected by perennial flooding from both coastal and riverine, which mostly leads to the loss of lives and damages of properties worth millions of Dollars. To aid in the flood management of the catchment, the annual maxima rainfall and flood and consecutive wet and dry days were subjected to the Gumbel extreme value distribution to estimate and predict the return periods of these variables and their magnitudes. The return periods under consideration include 5, 10, 25, 50, 75 and 100 years. Datasets for maxima rainfall and consecutive wet days (CWD) and consecutive dry days (CDD) were obtained from the CHIRPS product and the maxima flood time-series from 1975 to 2015 obtained from SWAT model simulations.

The results revealed that the magnitude of these hydro-meteorological variables would increase for these return periods. For instance, maxima rainfall would increase to 190 mm for the 100 year return period relative to the base (1981 to 2015) climatology within 1% to 20% probability. Maxima rainfall would decline northward with the highest obtained at the south-east of the catchment. Rainfall maxima is also expected to have a northward decline with higher maxima obtained at the south-east of the catchment. The spatial variation of the CDD and CWD had maxima reaching about 190 days and 28 days respectively and without any external influencing factors such as climate and anthropogenic activities for the 100 year return period. The flood frequency curve at the Birim, Offin and Main Pra sub-catchments showed that, for baseline maxima floods, the return periods of ≤ 20 years have magnitudes less than 3000 cms, 4000 cms, and 6500 cms for Birim, Offin and Main Pra respectively. The least floods at the Birim sub-catchment suggest higher stability in terms of flood resilience than Offin and Main Pra. An estimated 50% of the flood maxima at the sub-catchments had an exceedance probability in the range of 50 - 100%, which implies these events could occur in every 1 to 2 years.

Nonetheless, there exist limitations in this study, which includes the model uncertainties in the simulation of maxima floods and the assumption of no influence from anthropogenic and climate sources. Furthermore, there is an expected error rate of approximately ± 25% associated with the record length of the climatology datasets for projection between 10 to 100 year return periods. For risk assessment, it is imperative to consider that floods and maxima rainfall amounts are expected to increase in future years and the influence of external factors from human and climate is likely to alter the spatio-temporal variability slightly. In the current and near-future, attention should be on floods with higher occurrence probability with corresponding low return periods as these can lead to a recurrence of unexpected damages.

For future risk assessment, low probability floods should be taken into account as their magnitude and occurrence probability can become quite substantial. The expected rise in maxima rainfall with or without these external influences would surely also lead to flooding if adequate infrastructural measures are not put in place by policymakers and planners. Construction of hydraulic structures such as dams and reservoirs would be necessary to accommodate flooding events at the catchment. Overall, these results would aid water managers and planners especially at the water resource commission in the formulation and implementation of policies given the degree of risk associated with both current and future floods and rainfall at the catchment.

Author contribution statement

Marian Amoakowaah Osei: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Leonard Kofitse Amekudzi: Performed the experiments.

Akoto Yaw Omari-Sasu, Emmanuel Quansah, Kwasi Preko: Analyzed and interpreted the data.

Edmund Ilimoan Yamba, Jeffrey N.A. Aryee: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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