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Analysis of climate and anthropogenic impacts on runoff in the Lower Pra River Basin of Ghana

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Abstract

The Lower Pra River Basin (LPRB), located in the forest zone of southern Ghana has experienced changes due to variability in precipitation and diverse anthropogenic activities. Therefore, to maintain the functions of the ecosystem for water resources management, planning and sustainable development, it is important to differentiate the impacts of precipitation variability and anthropogenic activities on stream flow changes. We investigated the variability in runoff and quantified the contributions of precipitation and anthropogenic activities on runoff at the LPRB. Analysis of the precipitation–runoff for the period 1970–2010 revealed breakpoints in 1986, 2000, 2004 and 2010 in the LPRB. The periods influenced by anthropogenic activities were categorized into three periods 1987–2000, 2001–2004 and 2005–2010, revealing a decrease in runoff during 1987–2000 and an increase in runoff during 2001–2004 and 2005–2010. Assessment of monthly, seasonal and annual runoff depicted a significant increasing trend in the runoff time series during the dry season. Generally, runoff increased at a rate of $9.98 \times 10^7 m^3 yr^{-1}$, with precipitation variability and

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human activities contributing 17.4% and 82.3% respectively. The dominant small scale alluvial gold mining activity significantly contributes to the net runoff variability in LPRB.

Keywords: Hydrology, Environmental science

1. Introduction

Runoff phenomena of many rivers in tropical regions have changed markedly in the last two decades (Legesse et al., 2003; Syvitski et al., 2014). It has been hypothesized that variability in runoff occurs mainly from climate variability and human activities (Ma et al., 2010; Kliment and Matouškov, 2009; Wang et al., 2009; Ward et al., 2008). Climate change has caused increasing occurrences of extreme weather events and variability in precipitation resulting in increased runoff (Chen et al., 2006; Huo et al., 2008). Human activities such as alternate land use, deforestation, afforestation, construction of reservoirs, irrigation canals, dam construction, agriculture, mining, and domestic and industrial water usage have also led to significant changes in hydrologic processes especially runoff (Awotwi et al., 2015b; Yang and Tian, 2009; Sahagian, 2000). Water resources managers have been making significant efforts to protect the LPRB ecosystem by quantifying the contribution of climate variability and anthropogenic activities on runoff using long-term hydrologic data. Identifying variability in long-term hydrologic time series has scientific and practical importance to water resources management for flood control, water availability, river transport, hydropower generation and tourism (Kundzewicz, 2004).

The Pra River Basin is the second largest basin after the Volta basin in Ghana. The basin is of great importance due to its contribution to socio-economic activities that include agriculture, tourism and mining. The Pra River supplies fresh water to four out of the ten administrative regions of Ghana, serving over 4.2 million people. Most of the local households in the basin depend on groundwater both for domestic and commercial use as a result of unreliable supply from the Ghana Water Company Limited (GWCL). Apart from the conventional water treatment plants sourced from surface water, the GWCL has four additional water treatment plants sourced from groundwater located at New Edubiase, Dunkwa, Twifo Praso and Kibi. Thus, groundwater is considered very important by stakeholders in the basin.

Recently, the lower parts of the Pra River Basin have seen increased human activity which may have impacted on the runoff. Activities such as agriculture, logging, industrial water consumption and most importantly, illegal alluvial gold mining, known as “Galamsey”, are the main factors affecting the runoff change (Water Resources Commission, 2012). Beginning in the late 1990s, the government of Ghana placed a ban on logging by small scale chain-saw operators due to the high rate of deforestation and started to implement intensive

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afforestation measures. However as one activity was banned, another −small scale mining, known in local parlance as, “galamsey” operations also begun along the Pra River. Since the beginning of the 21st century, there have been rapid increases in human activities along the river as farmers sell their lands to “galamsey” operators or “galamseyers”, their accepted moniker. After mining activities are completed, though the miners are required by law to reclaim the land to about 75% of its original state, this is not done and in the instances where reclamation is done, the land is not conducive for farming. As a result, farmers are compelled to clear new forest zones for farming. This land use transformation affects surface runoff, stream flow and movement of sediment load into the Atlantic Ocean causing changes to the Pra River delta and ecosystem.

Many studies have been done on the hydrologic changes in river basins and their results revealed that human activity, land cover, climate variability and other indicators have affected runoff and sediment load (Awotwi et al., 2016; Guo et al., 2014; Fang et al., 2011; Ward et al., 2008; Zhang et al., 2008; Swank et al., 2001; Taylor and Pearce, 1982). Legesse et al. (2003) studied the responses of stream flow to land use changes and climate variability using the physically based distributed Precipitation Runoff Modelling System (PRMS) in the Ketar River Basin, North Africa. Their results revealed that decreasing rainfall will reduce stream flow from the catchment while increases in air temperature will result in a decrease in the catchment discharge. The results also showed that converting cultivated/grazing land to woodland in the river basin will result in decreasing discharge.

Awotwi et al. 2015a and 2015b assessed the impact of land-cover changes and climate variability on water balance components using the SWAT model in the White Volta Basin, West Africa. The results from Awotwi et al. (2015b) revealed that, as savannah and grassland are converted to farmlands, green water (evapotranspiration) and blue water (surface or groundwater runoff moving above and below the ground, respectively) increased and decreased respectively whilst results from Awotwi et al. (2015a) revealed that increases in precipitation and temperature resulted in increases in surface runoff, base flow and evapotranspiration. Both studies support water resources managers in protesting against farming close to water bodies and improving land management practices along the Volta River.

Zhang and Lu (2009) assessed hydrologic responses to precipitation variability and diverse human activities in a mountainous tributary of the lower Xijiang River in China using a statistical approach. The influences of precipitation variability and human activity on water discharge and sediment load were quantified using double mass curve and linear regression methods. Zhang and Lu showed that human activities contributed to about 80% of the increase in dry-season water discharge in the period 1969–2002. The results also revealed that human activities, particularly

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deforestation during the period 1981–1985 and 1986–2002, contributed 43% and 114% respectively to the increasing change of sediment load. The results for water discharge and sediment load in the study highlights the importance of monthly and seasonal time series in assessing variability in hydrologic processes. Ma et al. (2010) analyzed the impact of climate variability and human activity on stream flow in the Miyun reservoir catchment using a Geomorphology-Based Hydrological Model (GBHM) and a climate elasticity model. The results of the GBHM and climate elasticity model revealed that climate influence account for about 55% and 51% of the decrease in reservoir inflow respectively. The indirect impact of human activity accounts for an 18% decrease in reservoir inflow while the direct impact of human activity account for other percentage decreases in the reservoir inflow. Their study quantified the impact of direct and indirect human activity on river discharge, which is important in assessing stream flow.

The main aim of this study is to analyze and quantify the contribution of precipitation variability and human activity on runoff by investigating the changes in monthly, seasonal and annual time series of runoff and precipitation. This study provides in-depth understanding on the runoff responses to precipitation variability and uncontrolled alluvial mining activities which is critical for effective planning, management and sustainable development of programs to ensure water availability for present and future generation.

2. Materials and methods

2.1. Study Area

The LPRB is geographically located in the south-western part of Ghana (Fig. 1) and has a drainage area of 6,778 km^2. The LPRB is located within the Forest Ecological Zone of Ghana. Due to the recent increase in illegal small-scale alluvial gold mining activity, the forest has undergone rapid degradation. Mean annual runoff is estimated to be 4,200 m^3yr^{-1} (Water Resources Commission, 2012). The climate is considered to be Am, tropical monsoon climate, according to the updated Köppen-Geiger climate classification by Kottek et al., (2006). The LPRB has two rainy seasons, April-June and September-November. The mean annual rainfall of about 1,600 mm is relatively high. It, however, varies from 1,450 mm to 1,900 mm. The spatio-temporal variability of rainfall distribution is seen to increase towards the southern part of the basin. The average minimum and maximum air temperatures are 21 °C and 32 °C respectively. Air temperatures increase toward the northern part of the LPRB.

2.2. Data

Daily precipitation data from 1970 to 2010 at seven rain gauge stations within the LPRB and surrounding areas were obtained from the Ghana Meteorological

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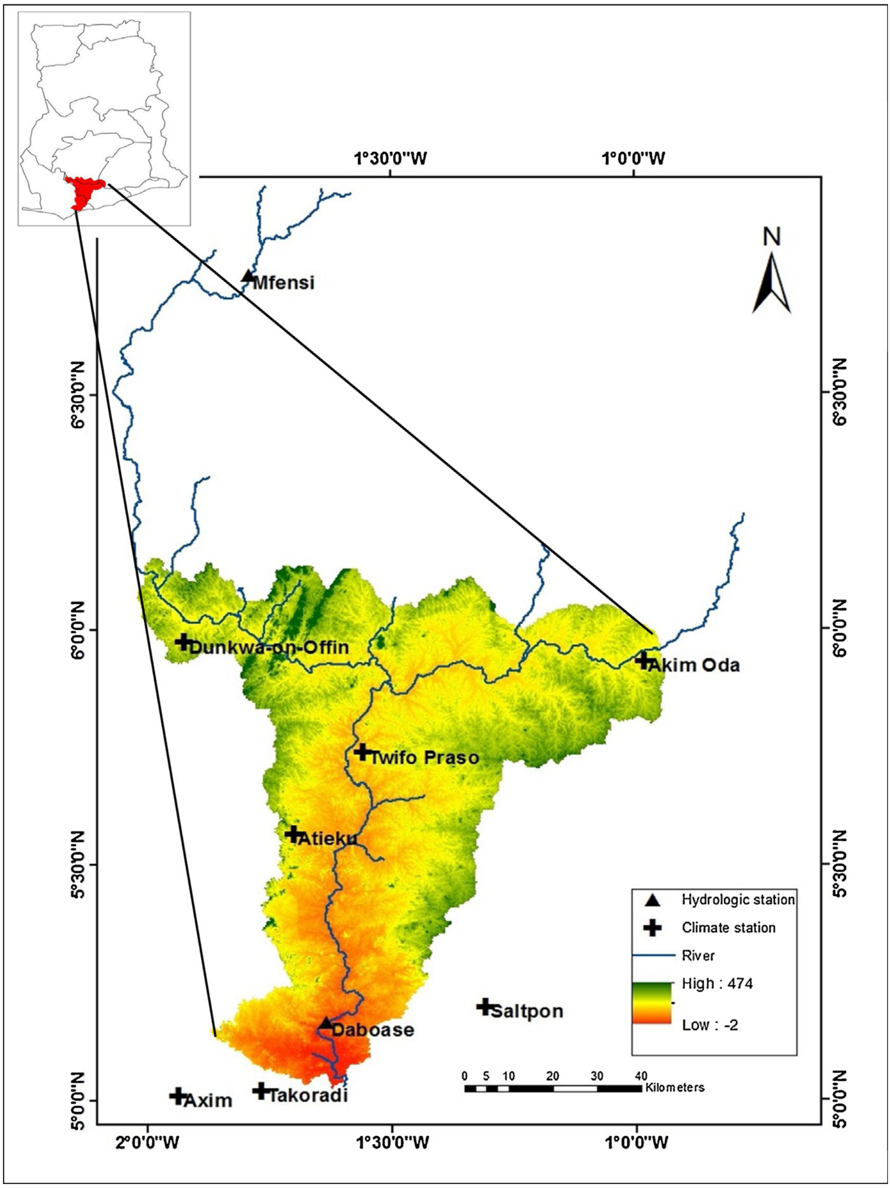

Fig. 1. Location of precipitation and hydrological stations of Lower Pra River Basin, Ghana.

Agency (GMet). The spatial mean precipitation for the monthly, seasonal and annual precipitation data were derived using the Inverse Distance Weighting (IDW) method. This method uses the exact distances between the estimation point and the known points to weigh their influence in calculating the estimated value. IDW was used because different distances are integrated in the estimation and the distance-weighting exponent is able to precisely control the influence of the distances. Daily discharge data from 1970 to 2010 at Daboase hydrologic station on the main Pra River were obtained from the Ghana Hydrological Service Department.

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2.3. Trends analysis

Time series analysis of precipitation data was performed to gain an understanding of the precipitation change. Since precipitation has major influence on hydrologic variability due to climate variability, it was considered as an index of climate for this study. Annual, monthly and seasonal trends in the precipitation data were analyzed. Non-parametric Mann–Kendall statistical test (Mann, 1945; Kendall, 1975), which has been widely used for assessing the significance of trends in hydro-meteorological time series, was employed for the trend analysis. This test was chosen due to its robustness for non-normally distributed data and its comparable power as parametric competitors (Serrano et al., 1999; Gao et al., 2011). The test is based on the Statistic (S) given by:

$$S = \sum_{i=1}^{N-1} \sum_{J=i+1}^{N} \operatorname{sgn}(x_j - x_i) \tag{1}$$

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1, if\ x_j > x_i \\ 0, if\ x_j = x_i \\ -1, if\ x_j < x_i \end{cases} \tag{2}$$

where x_i and x_j are the data values at times i and j, and N the length of the observation.

The positive and negative signs of the S value indicate the upward and downward trend of the datasets respectively, whilst S = 0 represents no trend.

The statistical significance of the trends can be tested by comparing the standard normal variation (i) value in Eq. (3) with the standard normal distribution Table at required significance level α. Under two-sided trend test, the null hypothesis (H_o) is rejected if $|Z| > |Z_{1-\alpha/2}|$. Otherwise H_o is accepted. In this study, a confidence level of 95% was adopted.

$$Z = \begin{cases} \frac{S-1}{\sigma}, S > 0 \\ 0, S = 0 \\ \frac{S+1}{\sigma}, S < 0 \end{cases} \tag{3}$$

$$\sigma = \sqrt{\frac{N(N-1)(2N+2)}{18}} \tag{4}$$

where σ is the standard deviation.

Since the test evaluates for a statistically significant trend, it is important to remove any data having serial correlation before performing the Mann–Kendall trend test (Miao et al., 2010). A Trend-Free Pre-Whitening (TFPW) method proposed by Yue et al., (2002) was adopted in the study to remove the effect of serial correlation.

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Autocorrelation was assessed by correcting the autocorrelation coefficients of the time series using only those with significant autocorrelation at the 0.05 significance level. The trend slope was estimated by using the Sen's slope estimator to investigate the stationarity of the autoregressive process. Sen's slope estimator is robust against non-normal distributions with missing data and extreme outliers (Sen, 1968). It estimates the trend slope (α) as the median slope between all possible pairs of observation as:

$$\alpha = \text{median}\left(\frac{x_j - x_i}{j - i}\right), 1 < i < j < N \tag{5}$$

where $i = 1, 2 \ldots N-1$ and $j = 2 \ldots N$.

Positive and negative values of α denote increasing and decreasing trend respectively.

Significant linear trend was removed from the raw times series data using Eq. (6).

$$Y_t = X_t - \alpha t \tag{6}$$

where Y_t is the detrended time series data at time t; X_t is the raw time series data at time t; and α is the slope estimator of the trend in the raw time series data.

Lag-1 serial correlation coefficient (l_c) was estimated using the equation proposed by Salas et al. (1980) as follows:

$$l_c = \frac{\frac{1}{n-1}\sum_{t=1}^{n-1}[X_t - E(X_t)][X_{t+1} - E(X_t)]}{\frac{1}{n}\sum_{t=1}^{n-1}[X_t - E(X_t)]^2} \tag{7}$$

$$E(X_t) = \frac{1}{n}\sum_{t=1}^{n} X_t \tag{8}$$

where l_c is the lag-1 serial correlation coefficient of the raw time series data, X_t; and E (X_t) is the mean of raw time series data.

The TFPW method was then used to eliminate the serial correlation from time series data using:

$$\mathbf{R} = \mathbf{Y_t} - \mathbf{l_c Y_{t-1}} \tag{9}$$

where R is the residual series

2.4. Change-point analysis

Identifying break points is essential for surface runoff analysis which aids in assessing the effects of climate variability and human activities. This study used Pettitt test and precipitation-runoff Double Cumulative Curve (DCC) to assess

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changes within hydro-meteorological series of LPRB. Pettitt's test is a nonparametric approach for determining the occurrence of a change point (Pettitt, 1979). It is used to reveal changes in time series data. The test is a rank-based and distribution-free test for detecting a significant change in the mean of a time series when the exact time of the change is unknown (Pettitt, 1979). The Pettit test is estimated by the formula:

$$U_{T,N} = \sum_{J=1}^{T}\sum_{i=1}^{N}\mathrm{sgn}(x_j - x_i) \tag{10}$$

where T = 1, 2, 3 . . . , N

The DCC is an x-y scatter plot with the cumulative quantity of one variable plotted against the cumulative quantity of another for a concurrent period (Searcy and Hardison, 1960). The idea behind the DCC is that a plot of two cumulatively variables will produce a straight line if the variables are proportional and the slope presents the constant of proportionality between the two variables (Searcy and Hardison, 1960). A change in the slope of the curve reveals that the internal relations between the two variables have been changed and provides important information about the activities surrounding the two variables. DCCs have been extensively used to analyze the relationship between hydro-meteorological variables such as precipitation–runoff, precipitation–sediment (sediment production and its relationship with climatic factor) and runoff–sediment (sediment production and its relationship with hydrologic factor). These relationships help to assess the impact of human activities on surface runoff and stream flow (Walling and Fang, 2003; Zheng et al., 2009). In this study, the DCC method was used to identify the points where human activities affected stream runoff. In the situation where the change point relates to maximum $U_{T,N}$, *Pettit's* test was deployed to determine the change point of runoff series to reaffirm the change point produced by the DCC.

2.5. Quantification of climate change and human activity on runoff

As changes in runoff are attributed to both climate change and human activity, the total change in runoff assumes that the effects of climate change and human activity on runoff are independent. Thus, the first-order approximation of the total change in the runoff (ΔR_{total}) is estimated by the formula:

$$\Delta R_{total} = \Delta R_{climate} + \Delta R_{human} \tag{11}$$

where $\Delta R_{climate}$ is the change in runoff due to climate variability and ΔR_{human} represents the change in runoff due to various anthropogenic activities.

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To quantify the impact of the climate change and human activities on runoff changes, the variability in the pre-break period and post-break period was assessed. The DCC was used to identify break periods. Consequently, the relative impact of the precipitation changes between pre-break and post-break periods on the runoff is estimated as:

$$\Delta \mathrm{R}_{\mathrm{precipitation}} = \frac{R_{calculated} - R_{observed}}{\left(R_{calculated} - R_{observed}\right) + \left(R_{obs-change} - R_{calculated}\right)} \times 100 \tag{12}$$

where $\Delta\mathrm{R}_{\mathrm{precipitation}}$ is the contributions of precipitation variability to changes in runoff; $\mathrm{R}_{\mathrm{observed}}$ is the mean of the observed annual runoff during pre-break period; $\mathrm{R}_{\mathrm{calculated}}$ is the mean of the calculated runoff; and $\mathrm{R}_{\mathrm{obs-change}}$ represents the mean observed runoff during the post period.

The $\mathrm{R}_{\mathrm{calculated}}$ was estimated by substituting the precipitation of the dry season in post-break period into the generated pre-break period regression equation of precipitation and runoff series on the condition of the runoff yield capacity of the pre-break period. The calculation of the runoff change as a result of human activities is obtained as follows:

$$\Delta R_{human} = 1 - \Delta R_{precipitation} \tag{13}$$

3. Results

3.1. Trend analysis of precipitation

The LPRB has historically experienced uneven distribution of precipitation, with 77.8% of the annual precipitation recorded in the wet season. Out of this, 68.3% is recorded in April, May and June. Results from Table 1 shows that there was no statistically significant decreasing trend in annual precipitation during the period 1970–2010. The Mann-Kendall test results cannot, however, conclude that there is no statistically significant trend because trends in precipitation at the annual level may not be identifiable. Hence, monthly and seasonal trend analyses were performed. Analyzed monthly trends indicated no statistically significant trends (Table 1) apart from February and March. The February and March precipitation exhibited decreased rate at 7.3 ×10 mm yr^{-1} and 1.08 mm yr^{-1} with their corresponding Z-values of −2.13 and − 2.61 respectively.

Hydrologic processes at downstream are altered by upstream actions hence an analysis was made on the annual and dry-season precipitation. Results revealed that over the period 1970–2010 (Figs. 2 and 3), the annual and dry-season precipitation systematically decreased across the entire upstream of the Pra River Basin with mean slope trend of 2.49 mm yr^{-1} and 2.81 mm yr^{-1} respectively.

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Table 1. Mann–Kendall test and Sen′s slope estimator results for precipitation over the period 1970–2010.

Mann-Kendall test					
	S	Z	Tau	p-value	b ($mmyr^{-1}$)
Annual time series					
Yearly	-105	-1.12	-0.12	0.260	-2.75
Seasonal time series					
Dry	-114	-1.31	-0.14	0.204	-1.89
Wet	-22.0	-0.20	-0.030	0.814	-0.453
Monthly time series					
January	100	1.12	0.12	0.266	0.194
February	**-192**	**-2.13**	**-0.23**	**0.032**	**-0.727**
March	**-234**	**-2.61**	**-0.29**	**0.009**	**-1.08**
April	28.0	0.33	0.03	0.762	0.185
May	22.0	0.23	0.03	0.814	0.265
June	-110	-1.24	-0.13	0.221	-1.469
July	25.0	0.31	0.03	0.795	0.266
August	-2.00	0.00	0.00	0.991	-0.013
September	16.0	0.12	0.02	0.866	0.125
October	146	1.59	0.18	0.103	1.448
November	2.00	0.00	0.00	0.991	0.233
December	-36.0	-0.38	-0.04	0.694	-0.094

Bolded row = significant trend.
+ increasing and − decreasing.

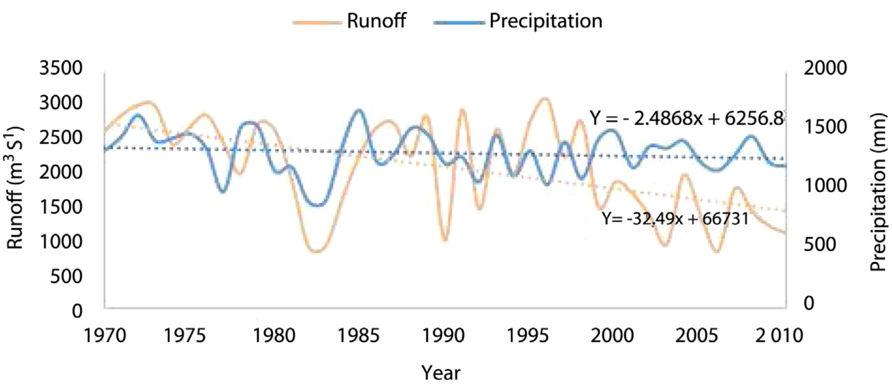

Fig. 2. Annual precipitation and runoff trend in the upstream of Pra River Basin for 1970–2010.

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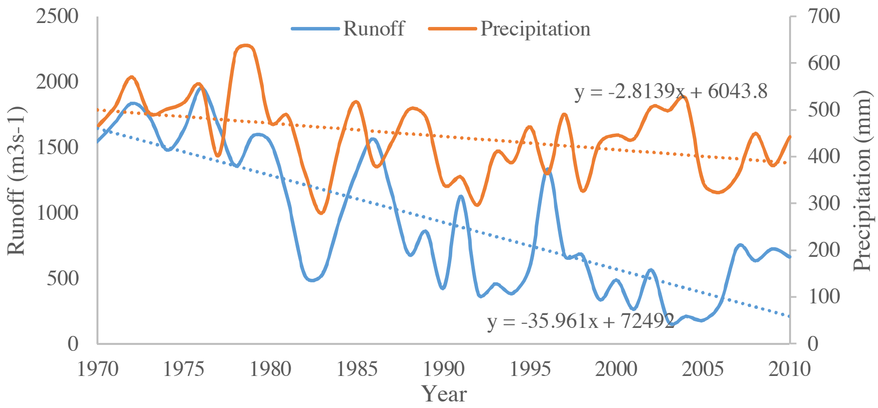

Fig. 3. Dry-season precipitation and runoff trend in the upstream of Pra River Basin for 1970–2010.

3.2. Trend analysis of the runoff

Trend analysis was used to analyze the climatic and hydrologic variability over a 41-year period. Statistical analysis was applied to the seasonal, monthly and annual runoff data from 1970 to 2010 to study the trends (Table 2). Annual water runoff

Table 2. Mann–Kendall test and Sen′s slope estimator results for runoff over the period 1970–2010.

Mann-Kendall trend test	S	Z	Tua	p-value	b ($m^3 yr^{-1}$)
Annual time series					
Yearly	**318**	**2.23**	**0.24**	**0.026**	**383.0**
Seasonal time series					
Wet season	110	1.22	0.13	0.221	151.0
Dry season	**240**	**2.70**	**0.29**	**0.007**	**284.0**
Monthly time series					
January	**246**	**2.83**	**0.30**	**0.006**	**24.5**
February	**224**	**2.51**	**0.27**	**0.012**	**20.8**
March	**232**	**2.61**	**0.28**	**0.009**	**40.6**
April	136	1.50	0.17	0.129	24.7
May	174	1.92	0.21	0.052	53.5
June	90.0	1.00	0.11	0.317	43.1
July	**118**	**2.06**	**0.22**	**0.039**	**58.5**
August	**152**	**2.34**	**0.25**	**0.019**	**82.3**
September	18.0	0.23	0.02	0.849	10.6
October	136	1.51	0.17	0.129	64.1
November	**202**	**2.34**	**0.25**	**0.024**	**76.4**
December	**280**	**3.11**	**0.34**	**0.002**	**49.0**

Bolded row = significant trend.
+ increasing and − decreasing.

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showed a statistically significant increasing trend of 4.65×10^{2} m^{3} s^{-1} with Z-value of 2.6 at 5% significance level. Even though the annual water runoff in the catchments increased, significant trends were found in the dry months of January, February, March, July, August and December. The rate of increase of runoff is 3.09×10^{2} m^{3} s^{-1} per year. Although November is classified with the wet season, there was significant trend in the annual water runoff. This may be due to the fact that the second part of the wet and dry seasons in the study area, respectively, ends and begins in November.

Annual runoff at the Mfensi station located at the upstream of Pra River Basin revealed an average of 1.98×10^{3} m3 s^{-1} for the 41-year study period. During the period, the annual runoff at the Mfensi station revealed decreasing trends with a rate of 3.25×10 m3 s^{-1} per year (Fig. 2).

3.3. Break point in the precipitation

The change points in the time series and the significant p-value for the corresponding change point are indicated in Table 3. The only change point

Table 3. Pettitt test results for precipitation time series over the period 1970–2010.

Pettitt test for break point				
	Kr	**p-value**	**Shift**	**Change point**
Annual time series				
Yearly	171	0.198	-	1983
Seasonal time series				
Dry	146	0.327	-	1984
Wet	108	0.742	-	1982
Monthly time series				
January	132	0.455	+	1983
February	**216**	**0.038**	**-**	**1983**
March	**220**	**0.033**	**-**	**1983**
April	80	1.160	+	1988
May	88	1.040	+	2004
June	138	0.396	-	1982
July	70	1.360	+	1975
August	74	1.260	+	1983
September	110	0.718	+	1995
October	146	0.327	+	1996
November	90	1.010	+	1980
December	164	0.203	-	1982

Bolded row = time series data showing significant shifts (abrupt change).
+ = upward and − = downward.

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occurred during the period when the country experienced severe drought in 1982 and 1983. The seasonal and annual precipitation depicted no statistical significant change point at the 0.05 significance level over the 41-year period. Significant abrupt changes for the monthly time series were detected around 1983 for February and March precipitations with p-value < 0.05.The remaining months showed no significant change point.

3.4. Break point in the runoff

Based on the Pettitt test results in Table 4, an abrupt change in the annual runoff was identified in 1985 and this is also depicted by cumulative residual in Fig. 4. The monthly time series with significant change periods can be found in the dry season and is prevalent in 1994 (Fig. 5). The earlier change point of the annual runoff depicted by the Pettitt test is as a result of the inability of the test to identify minor change in the beginning. The rate of runoff in the before-change periods and after-change periods were assessed to gain better understanding of the characteristics of the runoff change. The results from Fig. 6, indicated a downward

Table 4. Pettitt test results for runoff time series over the period 1970–2010.

Pettitt test for break point				
	Kr	**p-value**	**Shift**	**change point**
Annual time series				
Yearly	**260**	**0.006**	**+**	**1985**
Seasonal time series				
Wet season	1681	point	+	2010
Dry season	**226**	**0.026**	**+**	**1994**
Monthly time series				
January	**186**	**0.011**	**+**	**1993**
February	**190**	**0.093**	**+**	**1993**
March	**210**	**0.047**	**+**	**1995**
April	154	0.267	+	2002
May	202	0.062	+	1985
June	164	0.203	+	1981
July	140	0.378	+	2003
August	**162**	**0.215**	**+**	**1993**
September	**106**	**0.770**	**+**	**1994**
October	158	0.240	+	1978
November	**252**	**0.009**	**+**	**1993**
December	**210**	**0.047**	**+**	**1994**

Bolded row = time series data showing significant shifts (abrupt change).
+ = upward and − = downward.

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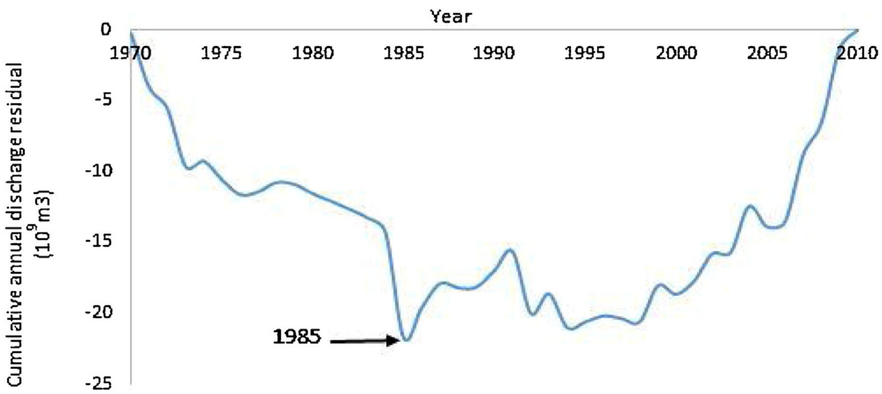

Fig. 4. Change point detection of annual runoff time series by cumulative residual method.

change from 1970 to 1985 and from 1986 to 2010 with annual runoff rate of $-4.4 \times 10^7 m^3 yr^{-1}$ and $1.0 \times 10^8 m^3 yr^{-1}$ respectively. The test also showed significant change in the dry season with an upward trend in 1994. The mean change in runoff is from $-0.028 \times 10^9 m^3 yr^{-1}$ to $0.131 \times 10^9 m^3 yr^{-1}$, which occurred in 1970–1994 and 1995–2010 respectively (Fig. 7).

3.5. Analysis anthropogenic activities

According to the land-use/land-cover data (Fig. 8), the LPRB underwent various land surface changes from 1986 to 2010. The classification revealed that within the period from 1987 to 2000, there has been significant land use changes in the basin with forest, cropland and settlement increased by 16.5%, 144% and 150%, respectively, while the open forest cover reduced by 41.6%. Alluvial mining activity in the basin was identified within the period 2001–2004 to be covering 3.55% of the total study area. Conversely forest and open forest reduced by 16.3% and 15.4%, respectively, and settlement, cropland and water use increased by 66.8%, 5.9% and 10.1% respectively, during the same period. The alluvial mining activity increased by 70.7% within 4 years (2005–2008) during which time the

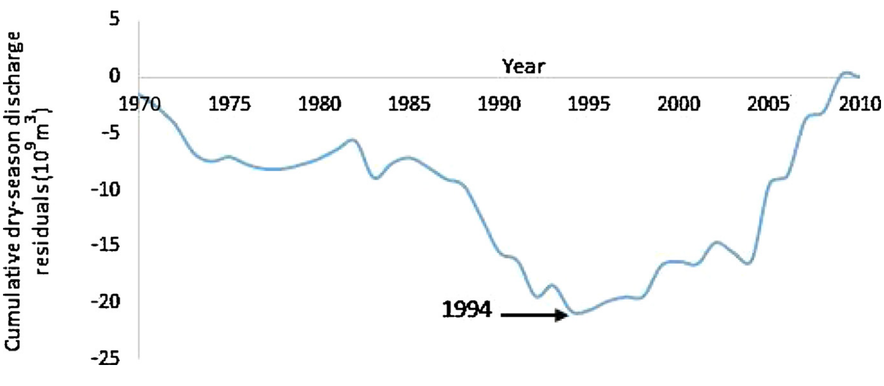

Fig. 5. Change point detection of dry-season runoff by cumulative residual method.

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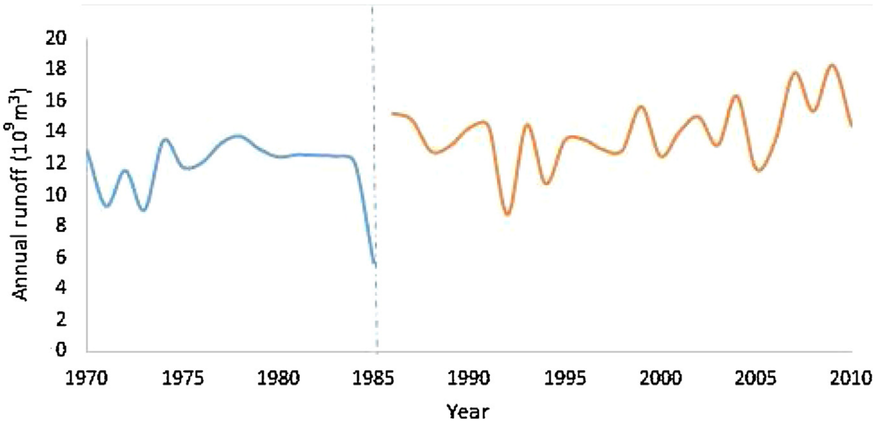

Fig. 6. Variation of the mean level in annual runoff of pre-break and post-break point at LBRB.

forest and open forest recorded reduction of 11.9% and 32.1% respectively, while the settlement, cropland and water use recorded increment of 20.0%, 30.1% and 19.9% respectively (Fig. 9).

The trend of the land cover changes in the upstream of Pra River Basin is similar to that of the LPRB. The only difference is that there is no alluvial mining activity at the river's upstream.

4. Discussion

4.1. Precipitation variability and human activities impact on runoff

The statistical tests results revealed significant trends and abrupt changes in the seasonal, monthly and annual runoff time series data for the LPRB from 1970 to 2010. Changes in runoff in the river basin can be attributed to the results of climate variability and anthropogenic activities. Anthropogenic activities and climate

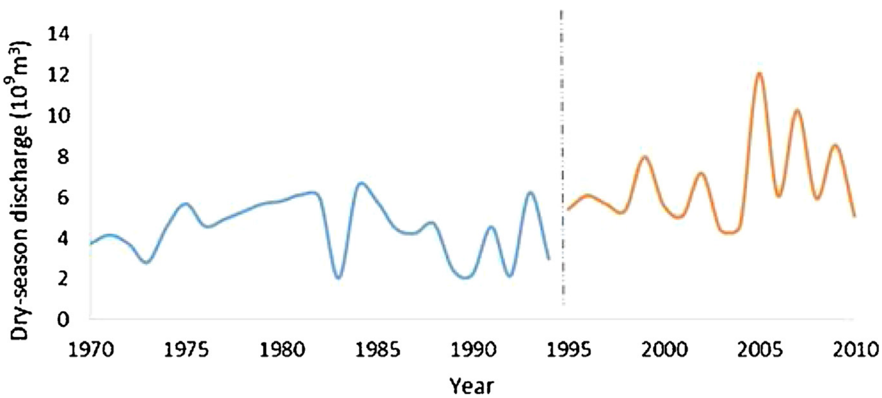

Fig. 7. Variation of the mean level in dry-season runoff pre and post change point of the study area.

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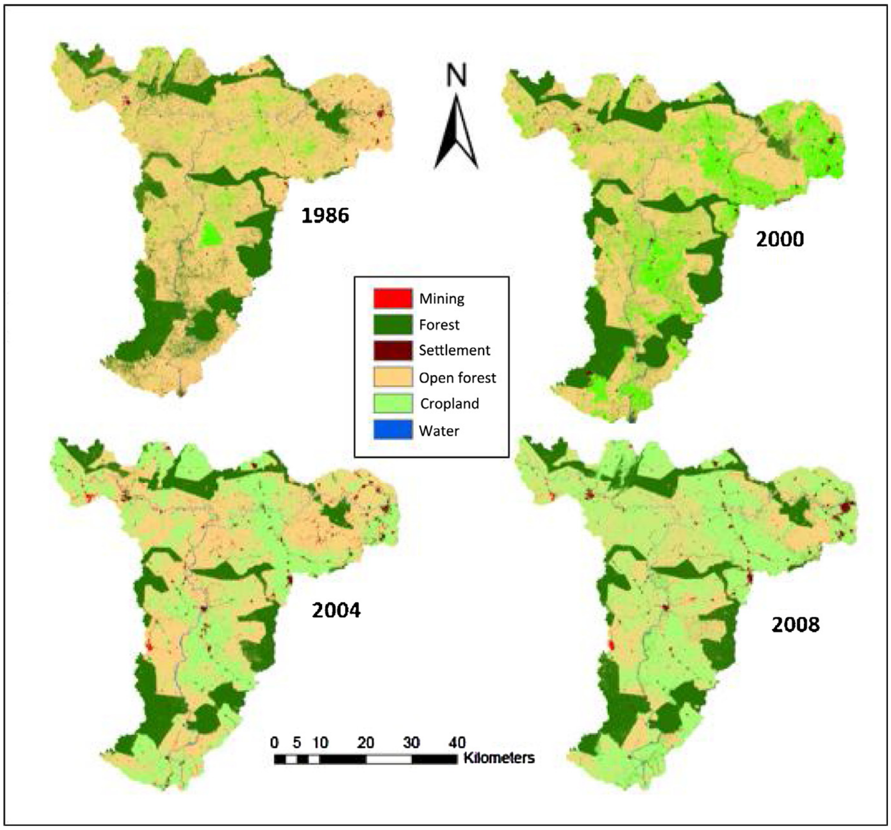

Fig. 8. Land surface change of the study area for 1986, 1998, 2004, and 2008.

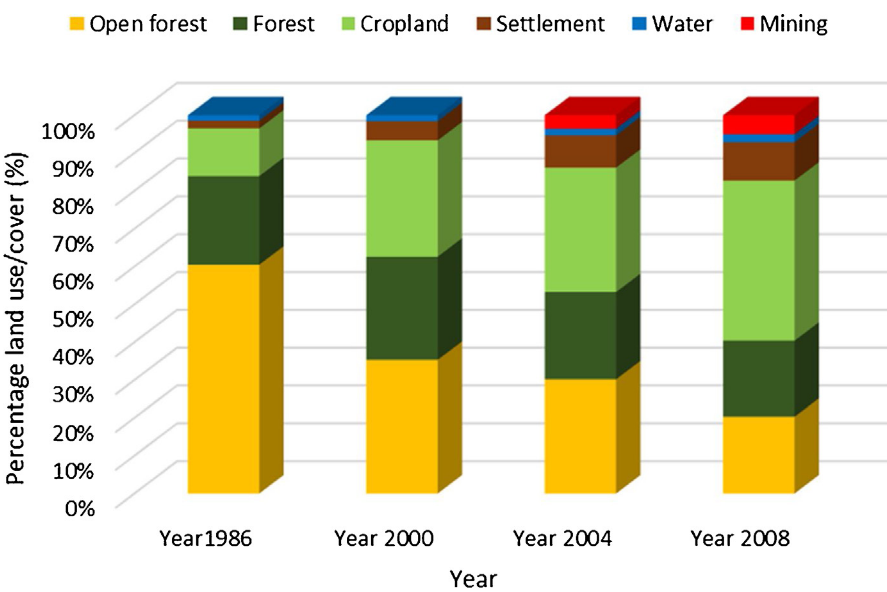

Fig. 9. Changes in the land cover of LPRB during the study period.

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variability are widely regarded as the two main driving forces of stream flow changes (Wang and Hejazi, 2011). Identifying the major driving force in runoff changes is critical to the stakeholders. This helps to plan and make managerial decisions concerning water security for the present generation while assisting in making water available for the future.

The declining precipitation and runoff trend upstream are expected to have an impact on the runoff downstream (Jiang et al., 2016; Nepal et al., 2014; Dong et al., 2012). Assuming land use changes and precipitation trends upstream become similar downstream, it is expected that the LPRB will exhibit decreasing runoff trends. This is however not the case as runoff trends downstream are opposite to that upstream. This may be attributed to the presence of alluvial gold mining activity at the LPRB

4.2. Contributions of precipitation and human activities to the runoff change

Since significant change in trends was identified in the dry season, the DCC was adopted in the dry season (Fig. 10). Without the influence of human activities on the hydrologic processes, the DCC exhibits a straight line which represents strong correlation between hydrologic variables and precipitation. Four change points in 1986, 2000, 2004 and 2008 were identified, according to the DCC and the t-test slopes comparison analysis (Table 5). These change points demonstrate that the variability in hydrologic processes in the basin were not only from climate but also as a result of anthropogenic activities. The change point in 1986 is similar to the change points identified in the Pettitt test and the cumulative residual curve. The precipitation-runoff cumulative curve was classified under five periods according to the slope change characteristics; Period 1 (P1) from 1970 to 1986; Period 2 (P2)

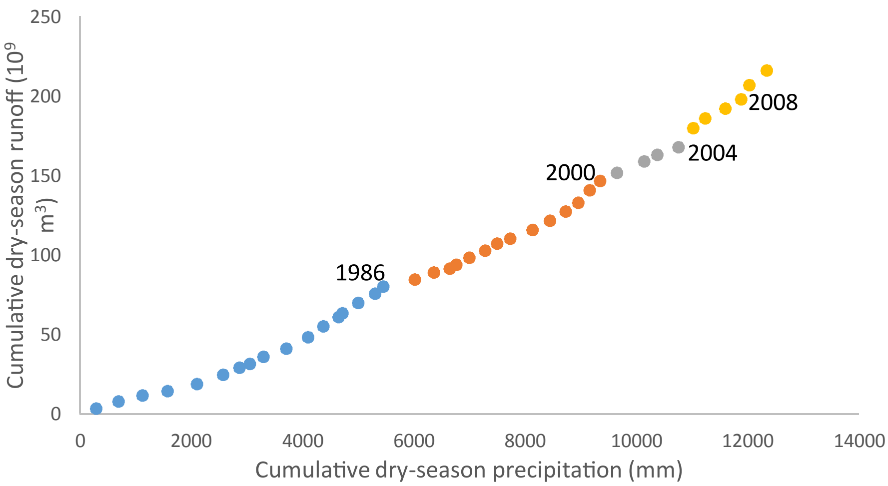

Fig. 10. Dry-season DCC between runoff and precipitation from 1970 to 2010.

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Table 5. T-test results for comparing slopes.

	$Slope_{P1andP2}$	$Slope_{P2andP3}$	$Slope_{P3andP4}$
Std err	8.91×10^{-4}	1.59×10^{-3}	2.11×10^{-3}
t	2.09	1.15×10	2.49
df	2.7×10	1.4×10	6.00
P-value	4.57×10^{-2}	1.62×10^{-8}	4.72×10^{-2}

Std err = standard error of the difference in slopes. $Slope_{P1andP2}$ = slopes of period 1 and period 2.
t = test statistic. $Slope_{P2andP3}$ = slopes of period 2 and period 3.
df = degree of freedom. $Slope_{P3andP4}$ = slopes of period 3 and period 4.

from 1987 to 2000; Period 3 (P3) from 2001 to 2004; and Period 4 (P4) from 2005 to 2010. The period P1, is the period where water discharge was not influenced by human activities. Thus, P1 was used as the reference period for the study. The change periods after the breakpoint are P2, P3 and P4. P2 recorded reduction in runoffs as compared to P1 (Table 6), which may be due to increased forest land reclamation as a result of the restriction placed on small scale chain-saw operations and the implementation of afforestation measures. Increase in forest land leads to high rates of evapotranspiration and hence a decrease in runoff (Spracklen et al., 2012). P3 is the period when afforestation activities were intensified. Compared to P1, there should be a decrease in runoff due to evapotranspiration (Ward et al., 2008). The opposite is however true (Table 6), and this can be certainly a direct result of the "galamsey" operations in the basin. The activity of "galamsey" operations leaves the topsoil clayey. This phenomenon prevents infiltration. Infiltration is impeded because the activity of surface mining as carried out by "galamsey" operators loosen the soil particles thereby creating gaps between the particles which are then filled by the clay particles of the new topsoil resulting from the mode of backfilling and gold extraction: the water used for washing the gravel which contain clay particles continuously run over the backfilled pits. Thus a surface seal is created which reduces infiltration rate. Also removal of vegetation cover (transformation of croplands and forest areas to mining area, Fig. 8) can form surface compaction of wet soils and also mechanically ruin the surface composition which can powder the soil surface during dry period. This tends to increase the rate of formation of surface seal during washing of haul gravel and raining period. (Agriculture Organization of the United Nations, 1993). Removal of vegetation cover also reduce evapotranspiration and increase runoff. Again according to the physical mechanism, runoff in the dry season is mainly attributed to base flow, whose rate depends on the pressure gradient between stream flow and groundwater since it affects the water movement resistance between the two hydrologic units thereby varying the intensity of the stream-aquifer water interchange (National Research Council, 1981). This means that as the "galamseyers" mine inside the

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Table 6. Quantification of the runoff changes in response to precipitation variability and human activities.

	Calculated (1)	observed (2)	Impact of precipitation only (10^9 m^3yr^{-1})		Impact of human activities only (10^9 m^3yr^{-1})	
			Value (3)=(1) − observed of reference	% = (3)/[(3) + (4)]	Value (4)=(2)-(1)	% (4)/[(3) + (4)]
1970-1986	4.67	4.72				
1987-2000	4.43	4.02	-0.293	41.6	-0.411	58.4
2001-2004	6.02	8. 28	1.26	36.5	2.26	63.5
2005-2010	5.90	8.24	1.18	33.4	2.34	66.6
1987-2010	5.08	6.79	0.360	17.4	1.71	82.6

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river, the resistance will be reduced and this will increase contribution of base flow to runoff. Therefore, increase in the runoff exhibited when P4 and P1 are compared, reflects the intensification of "galamsey" activities.

4.3. Estimation of climate variability and anthropogenic activities on runoff

To better understand the behavior of the changes in runoff, linear regression was used to assess the difference between the runoff during the pre-break and post-break periods in the dry season. Due to the non-monotonic nature of the runoff, linear regression equations between precipitation and runoff for the dry season were established for the various periods (Fig. 11). These were based on the change points identified in the DCC. The fitted lines for P3 and P4 lie above the one for P1 (Fig. 10). This implies that the runoff has recorded increments after 1986 as a result of anthropogenic activities. The position of the line of fit for P2, above and below the reference line showed both increase and decrease in runoff after 1986 due to the anthropogenic activities.

The linear regression equation between dry-season water runoff ($R_{\text{dry-season}}$) and dry-season precipitation ($P_{\text{dry-season}}$) in the pre-break period (1970–1986) is as follows:

$$(R_{dry-season} = 0.0031\,P_{dry-season} + 3.7315) \times 10^9 \tag{14}$$

Based on the linear regression equation (Eq. (14)), the impact of precipitation variability and human activities on the alterations of runoff were estimated (Table 6). Runoff in post-break periods was calculated by substituting the precipitation value of the post-break periods into equation 14. The difference between mean observed runoff in the pre-break period and the calculated values at

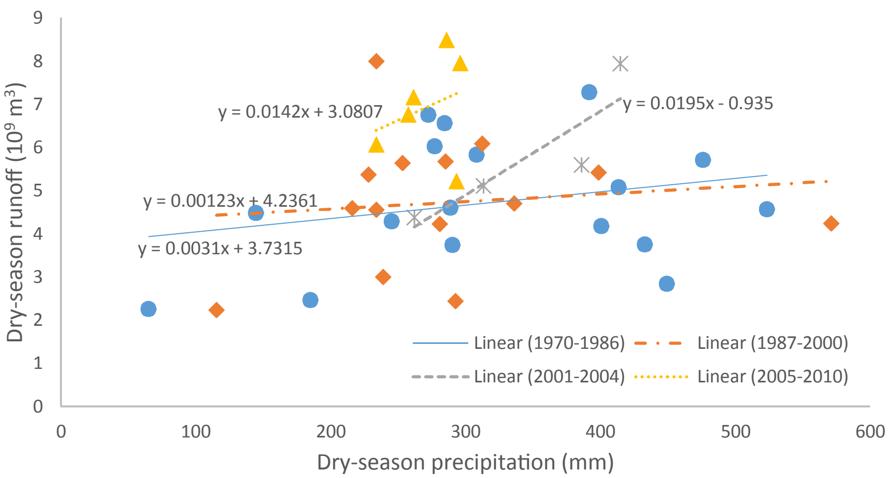

Fig. 11. Best-fitted lines of linear regression between dry-season runoff and dry-season precipitation.

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each period provided the estimated runoff change caused by precipitation alone. The impact of human activities on runoff change was assessed by differencing the measured values and calculated values in each period. During period 1987–2000, human activities and precipitation variability contributed 58.4% and 41.3%, respectively, to the reduction in runoff. However, marked increase in runoff was recorded in period 2001–2004 and 2005–2010. During period 2001–2004, contributions from human activities and precipitation variability were 63.5% and 36.5%, respectively, while the proportion of these contributors in period 2005–2010 were 66.6% and 34.4%, respectively. Generally, the period 1987–2010 depicted an increasing change, with human activities and precipitation variability contributing 82.6% and 17.4% respectively. Thus, human activities are the major factors causing runoff changes in the LPRB.

5. Conclusions

The monthly, seasonal and annual trends of the runoff in the LPRB depicted that the hydrologic processes have been greatly affected by precipitation variability and anthropogenic activity. The trends revealed that runoff is significantly increasing and has occurred mostly in the dry season. This can be attributed to the mushrooming illegal mining activity which has changed the soil structure, pressure gradient between stream flow and groundwater and vegetation cover. Abrupt change points were identified in 1986, 2000 and 2004. The period of the dry season runoff time series was divided into a reference period (1970–1986) and human-induced periods (1987–2000, 2001–2004 and 2005–2010). The result showed that precipitation variability and human activity like afforestation decreased runoff by 14.8% for the period 1987–2000. The contribution of precipitation variability and human activities to this change are 41.6% and 58.4%, respectively. For the periods 2001–2004 and 2005–2010, there was an increase in runoff at 75.4% and 74.4%, respectively. During the period 2001–2004, precipitation variability and human activities contributed 36.5% and 63.5% respectively to the change in runoff. During 2005–2010, precipitation variability and human activity contributed 33.4% and 66.6%, respectively to the change in runoff. As "galamsey" operations continue, the study area may in future experience flooding during periods of high precipitations due to the reduced infiltration rate. Therefore, reclamation activity by the "galamseyers" must be properly enforced and monitored and concurrently mining inside the river must be stopped.

The adopted research method and the linear regression model can be used to investigate and quantify the impact of changing environments on runoff in areas that lack historical data. This research assumed that precipitation variability and anthropogenic activities are independent. This assumption leads to uncertainties since precipitation variability and anthropogenic activities are connected. Future

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studies must consider these uncertainties to improve the quantitative estimation of impact of precipitation variability and human activities on runoff in the LPRB.

Declarations

Author contribution statement

Alfred Awotwi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Geophrey Kwame Anornu, Jonathan Quaye-Ballard: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Thompson Annor, Eric Kwabena Forkuo: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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