Relationship between Rainfall-Runoff on the White Volta River at Pwalugu of the Volta Basin in Ghana

Raymond Abudu Kasei[1,2], Boateng Ampadu[1], Guug Samuel Sapanbil[1]
1.University for Development Studies, P.O. Box 1186, Tamale, Ghana, Ghana
2.University of Bonn, Germany
E-mail of the corresponding author: *rkasei@uni-bonn.de*

Abstract
Rainfall and runoff patterns affect mans activities in so many ways and as such, designs of agricultural, storm water management, telecommunication, erosion, droughts, food security etc. It is essential that the role of rainfall and stream flow are recognized, understood and taken into account when modelling hydrological processes within any Basin. The Pwalugu catchment in the White Volta Basin experiences one rainy season which usually begins from April and peaks up in July, August, and September and gradually end with some showers in October and part of November. The basis of the analysis comprises of the rainfall events and runoff of the White Volta River at Pwalugu, to determine the relationship between the rainfall events and runoff and also estimates the contribution of rainfall to runoff by a certain threshold of rainfall. The analysis shows that the period is characterized by high inter-seasonal rainfall and discharge variability with a correlation coefficient of 0.78 which showed a strong positive relationship between rainfall and runoff in the catchment.
For the linear regression relationships of cumulated rainfall events and discharges for the various years considered for the study, it is realized that 2003 and 2009 recorded the highest coefficients of correlation of 0.96 and 0.92 respectively. The studies showed that the minimum rainfall that can cause runoff in the catchment is 25mm which was set as a threshold. It is also observed from the analysis that a rainfall of at least 18mm can contribute 0.2m^3/s of water to river flow with a correlation coefficient of 0.90 indicating a strong relationship between rainfall and riverflow.
Keywords: Rainfall, Runoff, Volta Basin, Intensity, Threshold

INTRODUCTION

Of all the earth's resource, none is fundamental to life than water. The restless atmosphere is an active agent in the constant redistribution of water on the earth surface, a fact that becomes even more striking when we realize that only a minute fraction of one percent of the earth's water is contained in the atmosphere at anytime. The seas and oceans contain about 93 percent of the earth's water; 2 percent is in the ice caps and glaciers; water bodies, groundwater, soil moisture and vegetation account for 5 percent (Howard, 1999).
Ungauged catchments are found in many parts of the world and largely in sub-Saharan Africa. Information collected in a gauged catchment and its regionalisation to ungauged areas is crucial for water resources assessment. Farmers in semi-arid areas such as Ghana are in need of such information. Inter and intra-seasonal rainfall variability is large in these areas, and farmers depend more and more on additional surface and groundwater resources for their crop production. As a result, understanding of the key hydrological processes, and determination of the frequencies and magnitudes of stream flows, is very important for local food production.
Rainfall pattern affects mans activities in so many ways and as such, designs of agricultural, storm water management, telecommunication, erosion and sediment control systems are highly dependent on rainfall characteristics. High intensity rainfall, particularly if sustained over a long duration, is mostly responsible for altering the geomorphology of a watershed and therefore, knowledge of the distribution of rainfall intensity is important in the design of erosion control and runoff conveyance systems
Several techniques have been used to assess the runoff response from different land uses. Brown et al. (2005) used the paired catchment approach whereby the runoff response of two neighbouring catchments with different land uses are analysed. Calder et al. (1995) used time series analysis of a catchment, including the "old" situation and the "new" situation. Differences in the runoff response are then attributed to the different land uses. The complication with using this method is that changes in the climate cannot be filtered out of the analyses and a long time series is necessary. Hydrological modelling is also often used to identify the possible changes in the runoff response of a catchment (e.g. Fenicia et al., 2008; Ott and Uhlenbrook, 2004) which have not been readily available largely due to technological gap that exist in regions such as Africa.
Rainfall in the region is erratic and unevenly distributed. Low rainfall in 1982/83 and 1997/1998, for example, saw water levels of reservoirs dropping to minimum operating levels and causing severe cuts in hydropower production and supply in Ghana in particular (Amisigo, 2005). Analyses of rainfall data from various stations within the Volta River system indicate that the months in which precipitation exceeds the evapotranspiration to generate runoff and direct recharge are usually June, July, August, and September (Kasei, 2010). This need to be

taken into consideration for a sustainable water resource management. It is essential that the role of rainfall and stream flow are recognized, understood and taken into account when modelling hydrological processes within the White Volta basin.

The portion of precipitation or irrigation waters that moves across land as surface flow and enters streams or other surface receiving waters as runoff occurs when the precipitation rate exceeds the infiltration rate. Runoff a general term in hydrology include surface runoff, also called overland flow a major hydrological tool used by hydrologist in the analysis of available water as well as water that make it way to stream channel just below the surface sometimes called interflow or base flow. Below is a Schematic landscape segment (Figure 1) showing the various components of runoff.

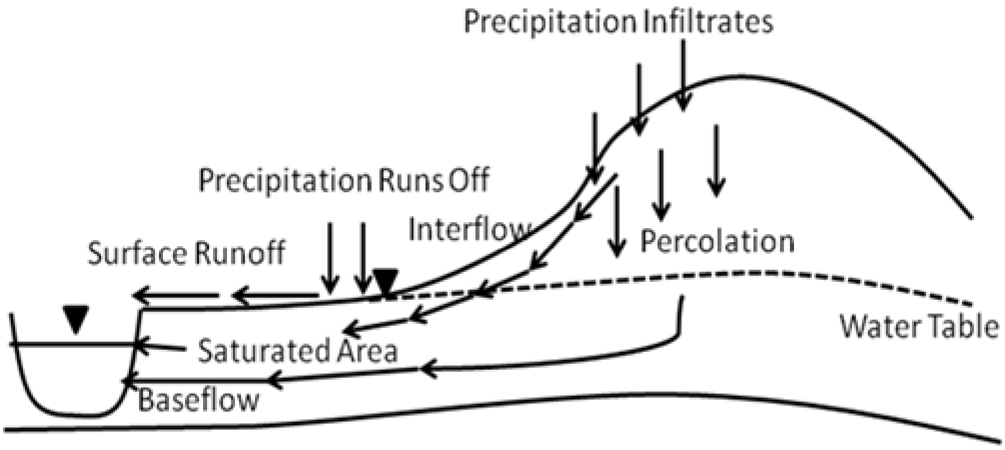

Figure1.Schematic landscape segment showing runoff components

Runoff, a component of the hydrological cycle, is considered an important process in the study of hydrology. Knowledge about runoff components (surface and channel flow) under changing climatic and vegetation condition in the White Volta River catchment is limited (Nyarko, 2007). Information about runoff is fundamental to the understanding of part of the hydrological processes in the catchment (White Volta River basin). For instance, runoff contributing to stream flow from all parts of the catchment is an important factor in meeting its water volume standards in the main Volta River and Akosombo dam.

Overland flow significantly influences the amount of water available in the rivers, streams and ponds, and determines the size and shape of flood peaks (Troch et al, 1994), when studied and properly managed, could be converted into valuable water resources for agricultural production in floodplain farming (Nyarko, 2007).

Understanding and modelling of surface runoff processes, requires the selection of appropriate spatial and temporal discretization, to reduce scale discrepancies, between observation and application (Ajayi, 2004). Hydrological modelling is very expensive in developing countries due to lack of computer resources and spatially distributed data due to the presence of ungauged and data limited catchments. This calls for the development of an alternative approach for the rough estimation of runoffs from rainfall in such areas. This study presents a tool for estimating runoffs which seeks to establish a relationship between runoffs and rainfall which could be used to solve runoff estimation problems, especially in ungauged catchments.

Study Area

The Pwalugu area which is the selected catchment is differentiated by its location through the Sudan Savannah ecology to the Guinea Savannah ecology situated in the Northern part of Ghana within the Volta Basin (Figure 2). Rainfall in the area is dependent on the seasonal northward movement of the inter-tropical convergence zone and reaching its peak on many occasions in August in the Sudan ecological zone and September in the Guinea Savannah zone. The moisture situation reduces with increasing Latitude therefore the Sudan ecology receives less rainfall than the guinea Savannah ecology and it is punctuated with dry spells of different durations. Small scale peasant farming is the main occupation of the people in the selected ten districts with small holdings of livestock. The Sudan ecology has a population of about 200 persons per square kilometre and the Guinea ecology has a population of 17 persons per square kilometre. Cereals are the staple food of the communities in the Savannah area. The main food crops cultivated in the area are rice, yams, groundnut, cassava, maize, sorghum, late millet, cowpea, pigeon pea, cotton in the Guinea Savannah and late millet early millet, cowpea, groundnut, sorghum, early maize, rice in the Sudan ecology (Kasei *et. al.*, 1995). Cereal production is the dominant agricultural activity in this semiarid environment. Cropping patterns in the ten districts differ and the most notable difference being the increasing dominance of millet and sorghum over maize and root crops as soil fertility.

An important difference among farmers of the catchment area in terms of food security comes from the constraints peculiar to the region and not from differences in farmer aspiration and these includes higher incomes, effort reduction and risk avoidance. This means that enough grains be harvested by November to feed their families until the beginning of the July/August early millet or maize harvest that provides food to fill the "hunger - gap" and that is the period most farmers have no cereal stocks.

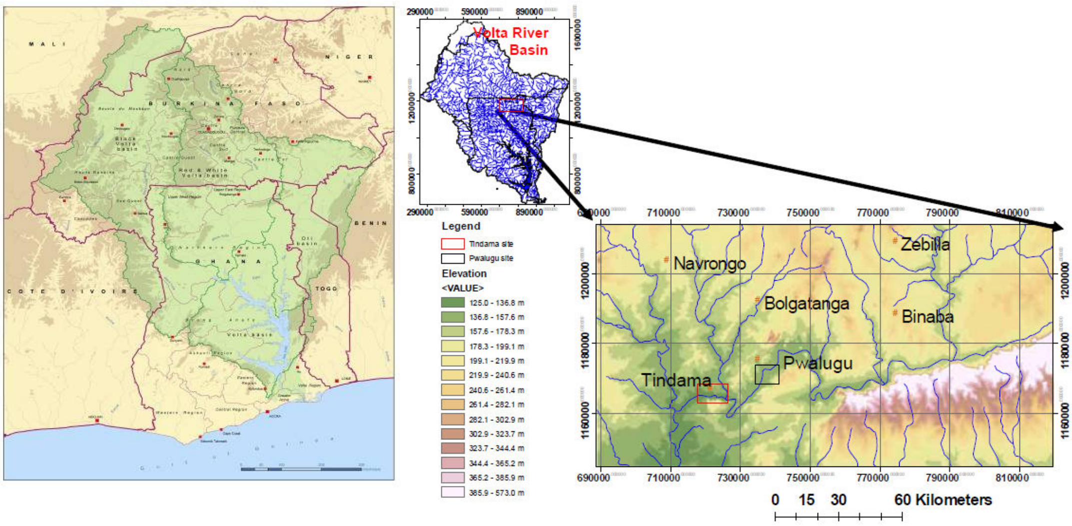

Figure 2. Pwalugu area of the White Volta River catchment within the Volta Basin

METHODOLOGY

Rainfall and Runoff relationship

Rainfall is viewed as the driving force in a rainfall - runoff relationship. It is always after a rainfall at a particular period of time (concentration of rainfall) that runoff is seen. When rainfall occurs, some of the rain drops are intercepted by leaves and stems of trees known as interception storage. The rest of the rain drops reach the surface of the ground where water begin to infiltrate into the soil. Once infiltration is started, it will reach a certain period of time where the soil become saturated (i.e. the rate of rainfall intensity exceeds the infiltration rate that the water begin to run on the surface known as surface runoff). The time interval used in the measurement of the two variables and the size of the area being considered can affect this relationship. There are also other physiographical factors which have a direct bearing on the occurrence of rainfall and the volume of runoff which are presented.

Rainfall intensities threshold

When rain fall in a catchment for a particular period of time, it generates runoff but not every single rainfall contributes to runoff. This may be due to the initial condition of the soil or the amount of rain falling at that particular period. The minimum amount of rainfall in an hour or a day that contribute to runoff for a known period of time is said to be the threshold for that particular catchment. The threshold depends on the physical characteristics of the area and varies from catchment to catchment. In areas with only sparse vegetation or a pavement such as a stretch of a motor way and where the land is very regularly shaped, the threshold may be very small while in other catchments where the prevailing soils have a high infiltration capacity; it may take a large amount of rainfall to contribute to runoff indicating that the threshold will be very high.

Relationship between the rainfall events and runoff

The basis of the analysis comprises of the rainfall events and runoff of the White Volta River at Pwalugu. However, for this particular study, the emphasis is more on the determination of the relationship between the rainfall events and runoff and also the estimation of the contribution of rainfall to runoff by a certain threshold rainfall events. The events analysis involved constructing of hydrographs to find the correlation of the amount of rainfall and the contribution to runoff during the storm and then set a threshold to find the contribution of rainfall to runoff. Rainfall events data were taken from a period of 2003-2009 and the corresponding river heights excluding 2005 (missing). With Microsoft excel, the data were critically analysed.

RESULTS AND DISCUSSIONS

Figure 3 presents a general distribution of rainfall and discharges for the 6 years period. The figure shows that the discharges generally increase with increases in the rainfall events while in some days, discharge increases as a result of upstream flows. It is observed that the rains mostly fall in the months of June, July, August, and September with its corresponding discharges increasing in that order. It is observed that from 2003-2009, the highest river flow was recorded in 2007 with a discharge of 1306 m^3/s and also 2008 showed a similar trend. Figure 3 indicates that the number of days with more rainy days and high discharge values were recorded in 2007, 2008 and 2009 which suggest flood years. However, the gaps in the hydrograph depict missing data for some days in the various months.

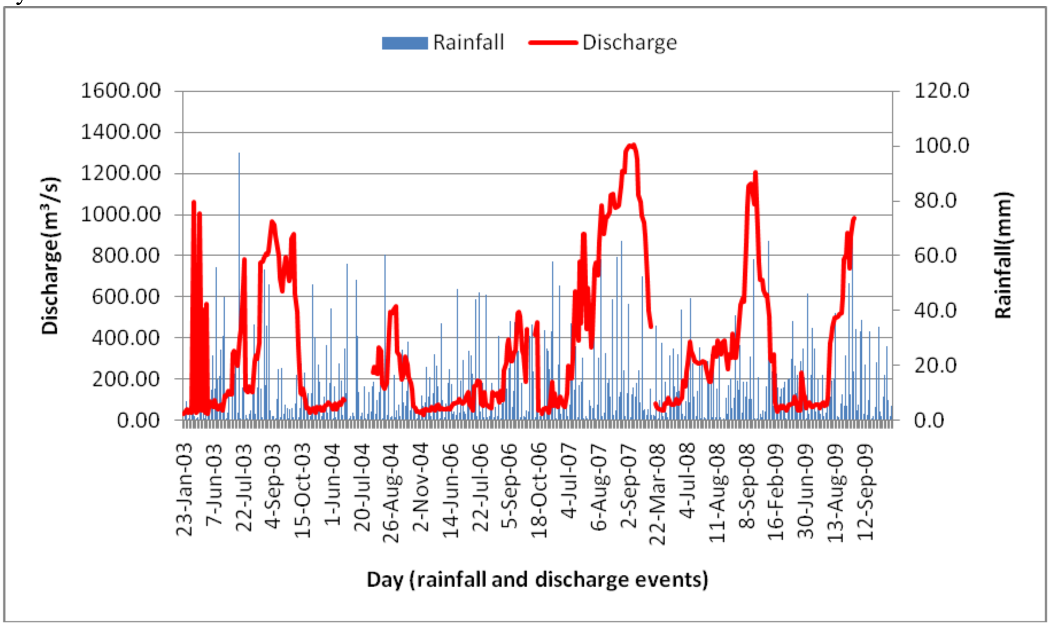

Figure 3. Distribution of rainfall- river discharges from 2003-2009 excluding 2005 of Pwalugu in the White Volta basin

A linear relationship, with a coefficient of determination of 0.611, (r^2 = 0.611) defines the relationship between the total rainfall events per month and the monthly discharge total of the 6 year period. However, the general correlation graph for the period considered for the study and some particular years considered are better correlated years, with a summary of regressing values for all the years as explained in figure 4.

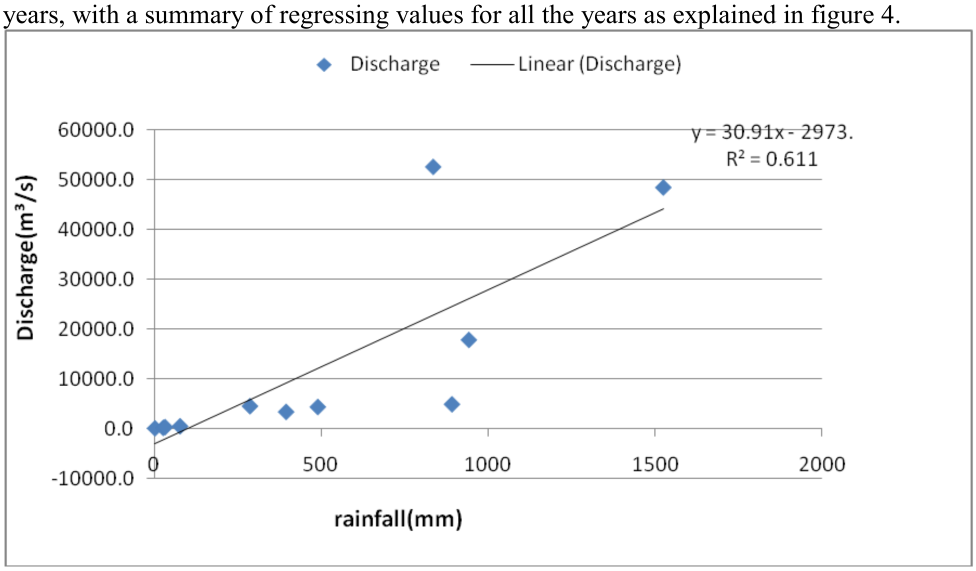

Figure 4, Relationship between the cumulated Rainfall and Discharges of 2003-2009 of the White Volta River at Pwalugu

The period is characterized by high inter-seasonal rainfall and discharge variability with a correlation coefficient of 0.78. This coefficient shows that there is a strong relationship between rainfall and runoff. The coefficient of determination (r^2 = 0.611) indicates that 61% of the variation in the discharges is accounted for by the variation in the rainfall events.

However, linear regression relationships of cumulated rainfall events and discharges were done for the various years considered for the study. It is observed that all of them showed positive correlations with some years showing high correlation coefficient values indicating high variations in the rainfall and the river discharges.

The graph (Figure 5) gave a strong correlation of r = 0.96 with a coefficient of determination, r^2 = 0.93. This means that there existed a strong relationship between rainfall and runoff. Generally, it is observed that August and September recorded high flows with even low rainfall events which might have been due to spills from upstream reservoirs such as the Bagri Dam in Burkina Faso.

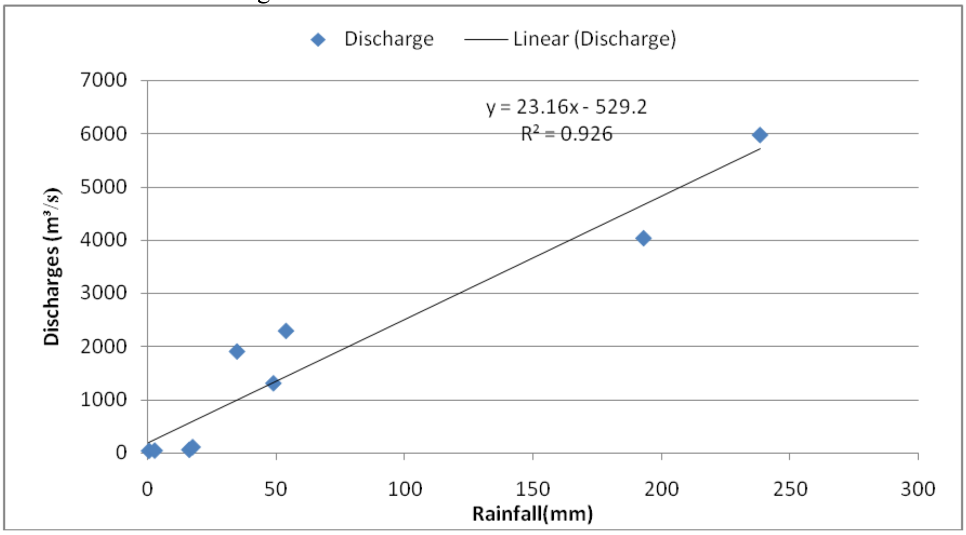

Figure 5. Cumulated Rainfall and Discharge relationship of 2003 of the White Volta River at Pwalugu

In Figure 6, it is observed that a high correlation coefficient of 0.86 is recorded signifying a strong relationship between the discharges and the rainfall with a value of the coefficient of determination of r^2 = 0.74 which indicates that 74% level of the variation is accounted for by the model equation. In figure 3, it is clearly shown in the distribution graph that 2007 recorded more and high number of rainfall events which made the corresponding discharge also high and recording the highest peak discharge among the 6 year period considered for the study. The statistical relationship established explains that the high rainfall events is responsible for the high flows recorded in the river which suggest that 2007 is one of the possible flood years recorded in the catchment. From the linear regression equation, it can be deduce that a minimum monthly total rainfall that can cause an increase in discharge is 25mm.

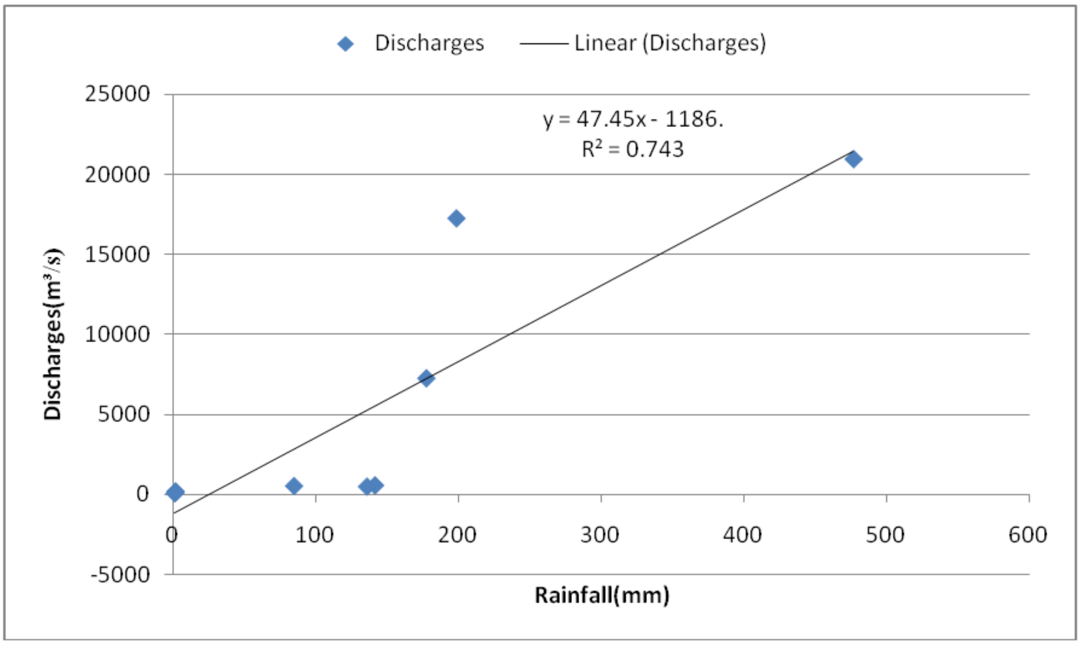

Figure 6, Cumulated Rainfall and Discharge relationship of 2007 of the White Volta River at Pwalugu

In 2008 (Figure 7), the coefficient of determination of r^2 =0.75 is the relationship level between the rainfall and discharges. However, the graph gave a high positive correlation of r= 87. This means that there existed a strong relationship between rainfall and runoff. The relationship further deduce that the minimum rainfall for this particular year that can cause an increase in the river discharge is 33mm of rain.

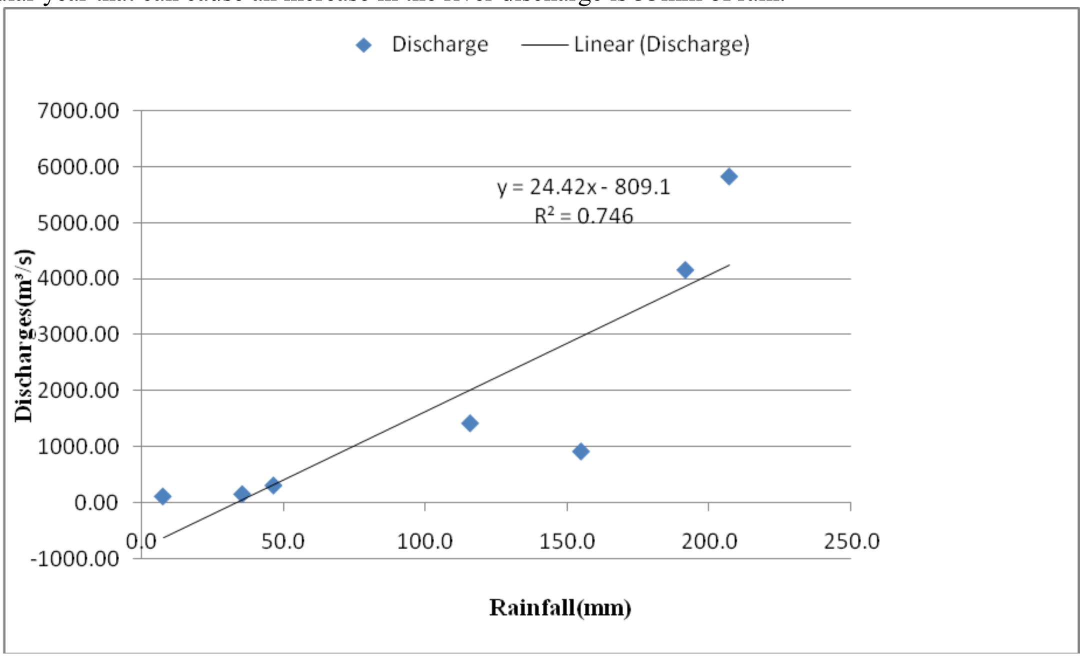

Figure 7. Cumulated Rainfall and Discharge relationship of 2008 of the White Volta River at Pwalugu

Below is a table of the summary of the minimum rainfall that can cause runoff, coefficients of correlation and determination for the various years from which a threshold is set.

Table 1 statistical values

Year	Coefficient of determination (R^2)	Correlation coefficient ($\sqrt{R^2}$)	Minimum Rainfall to cause runoff **Runoff (y) = (k) × Rainfall(x) –c**
2003	0.93	0.96	23mm
2004	0.66	0.81	23mm
2006	0.67	0.82	8mm
2007	0.74	0.86	25mm
2008	0.75	0.87	33mm
2009	0.85	0.92	35mm
2003-2009	0.61	0.78	Average = 25mm

Amount of Rainfall that Contribute to Runoff

Analyzing the contribution of rainfall to runoff, 20 rainstorms were selected out of the six years period on a threshold of 25mm rainfall intensity. Out of these, 11 rainstorms were also selected as best contributing to runoff based on the close interval of the rain days. The graph of contribution to runoff (m^3/s) and rainfall (mm) indicate a good correlation with R^2 of 0.81 and a correlation coefficient of 0.90. This correlation coefficient showed that there is strong relationship between rainfall and its contribution to runoff in the catchment. The linear regression is exhibited in figure 8.

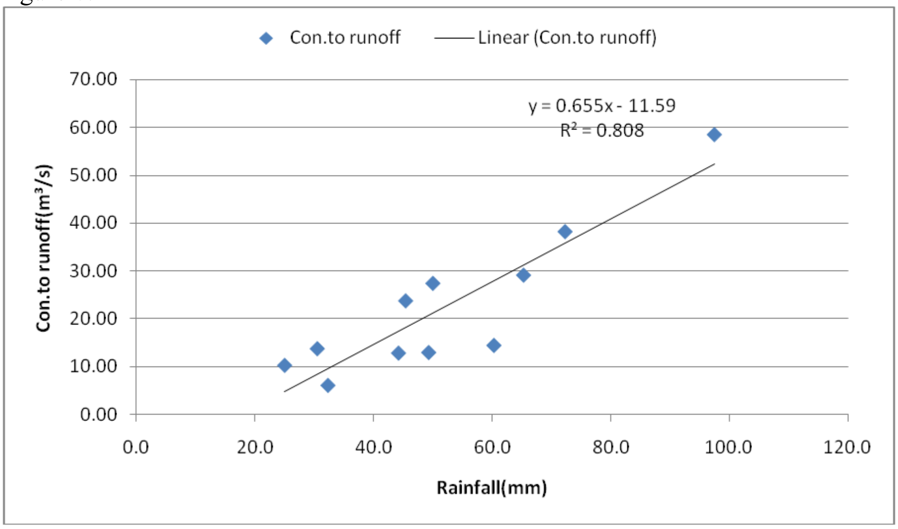

Figure 8, Rainfall contribution to runoff and rainfall relationship of the White Volta River at Pwalugu

Regressing rainfall against rainfall contributions to runoff (Figure 8) results in a simple model:

Contribution to runoff (y) = 0.655 x Rainfall (x) – 11.59,

With an **r²** value of 0.81, this regressing equation suggests that a minimum rainfall of 18mm of rain add to the river before a significant amount of runoff occurs. This means that at least 18mm of rainfall can contribute to runoff in the catchment which also falls within the Dubreuil (1985) threshold of rainfall for certain soil properties. Generally it is observed that the rains mostly fall in the months of June, July, August, and September with its corresponding discharges increasing in that order, this may be attributed to the saturation of the soils as the rainy season stabilizes. The period considered for the study is characterized by high inter-seasonal rainfall and discharge variability with a correlation coefficient of 0.78, indicating that there is a strong relationship between rainfall and runoff.

All the years showed high positive correlation as shown in table 4.1 which means that there exist a strong relationship between rainfall events and runoff with 2003 and 2009 recording the highest coefficients of correlation and determination. From the linear equations established it is found out that some minimum monthly totals of rainfall events are required to make a change in river discharge from which a the threshold was set as the average minimum rainfall to cause runoff for the various years of analysis. In finding the amount of rainfall that contributes to runoff in the catchment, a graph of some rainfall events and their corresponding discharges were plotted and it gave a linear equation of $y = 0.655x - 11.59$, where y and x are the dependent and independent variable respectively. This explains that the minimum rainfall that contributes to runoff is 18mm.

CONCLUSION AND RECOMMENDATION

This study showed that rainfall and runoff events play important roles in hydrological processes in the catchment.

From the general distribution of rainfall and discharge in the catchment, the study showed that rainfall is increasing in succeeding years and also a corresponding increase in the discharges which 2007 recorded the highest rainfall events and amount.

The regression analysis for the catchment indicates that it is characterized by high inter-seasonal rainfall and discharge variability with a correlation coefficient of 0.78. This correlation coefficient showed that there is a strong relationship between rainfall and discharge (runoff). However, the yearly regression analysis showed that 2003 and 2009 recorded very strong correlation coefficients of 0.96 and 0.92 respectively and 2004 recording a lowest coefficient of 0.81. The high coefficients for some of these particular years indicate that the high runoffs observed were as a result of the high rainfall events which could have accounted for floods in some of these years, for instance, 2007, 2008 and 2009.

From the study, the amount of rainfall that contributes to runoff in the catchment is about 18mm. This means that for rains in the catchment that fall above a threshold of 25mm of rainfall intensity can contribute at least 18mm of rain to runoff depending on the conditions at the time of the storm.

The study suggest that Dubrelil (1985) rainfall threshold values for some soil properties might work for the catchment since the threshold established from the study falls within the Dubrelil's threshold values of soil properties similar to the catchment. Overall, the objectives of this study have been achieved. The rainfall and runoff relationship was successfully developed and the amount of rainfall that contributes to runoff in the catchment also established.

There is the need for rainfall intensities to be measured for such studies rather than daily rainfall which has no idea of intensities and further studies should be carried out on rainfall intensities and contributions to runoff in the catchment and the Basin as a whole.

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