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Surface Runoff Responses to Rainfall Variability over the Bida Basin, Nigeria

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Abstract

Information on annual, seasonal, monthly and daily rainfall variation is desirable for planning operation and management of water resource projects as this gives an insight into river flow regimes. A surface runoff response to rainfall variation in The Bida River Basin was investigated. The River Basin has an area extent of about 7,540 km^2. The research utilizes rainfall data for a period of 30 years (1980 – 2009) mean, standard deviation, coefficient of variation and linear regression are used in the analysis. Results indicate that the rainfall pattern is generally in the form of alternating dry and wet years, and characterized by strong seasonality which is reflected in the surface runoff. Declining trend in rainfall over the years has been observed during the study period and is also reflected in the overall decline in runoff leading to variability in annual flow regimes. Therefore, attention should be focused on development of networking of continuous observation and monitoring of hydrometeorological variables and also control of environmental factors that influence the hydrology of the Bida Basin.

Keywords: Rainfall, Runoff, Landscape, Streamflow, Seasonality

1. Introduction

Rain falling on the landscape may flow quickly over soil or rock surfaces as runoff to stream channels. Alternately, some water may flow more slowly down slope toward streams within the soil. Some may percolate downward through pores in soil and fractures in rock to reach the top of the saturated zone (often called the Water Table). Below the saturated zone, it flows much more slowly as groundwater. Soil characteristics, plants and animals, and slope angle are among the natural factors controlling the proportion of precipitation that is converted to runoff in a given landscape, and the time it takes for runoff to enter a stream. Human changes to these landscape features can greatly influence runoff.

Linsley et al. (1958) opined that runoff may be produced when precipitation or snowmelt adds water to the soil surface faster than it can be absorbed. The excess water remains on the surface and flows down slope as runoff. In humid areas with greater vegetation cover, the water table may lie at the surface in low-lying areas or slope hollows, so that the soil there is saturated. Saturated areas expand during rain or snowmelt, as well as during the cold season when plants withdraw little water from the soil. Any rain that falls on these saturated areas must run off over the surface. In times of prolonged heavy rainfall, large areas of a gently sloping landscape may become saturated, and much of the rain that follows runs off rapidly to streams (Sharma et al., 1986).

Infiltration rate is controlled by the nature of the soil, by the plant and animal communities it supports, and by human influences. Where soil is absent and little-fractured bedrock is exposed, water cannot soak in and will run off rapidly. If soil is present, but is very fine-grained and clay-rich, the pore spaces that water must pass through are extremely small; hence, water will infiltrate very slowly compared to sandy soils that readily soak up water. Some finer-grained soils have vertical cracks that form when the soil shrinks as it dries. These cracks allow water to enter more readily, but may close up after the soil is wetted. Compaction of soils reduces the size of pore spaces and the infiltration rate. Water commonly runs off areas that were compacted through repeated passage of people, large animals, or heavy machinery. Raindrops falling on bare soil also can compact the soil surface in plowed fields, leading to increased runoff and erosion of farmland.

In general, plants and small animals tend to increase the infiltration rate of soils. When the landscape is completely devegetated, for example, following a forest fire or during a construction project, a dramatic increase in runoff and soil erosion may result. In desert environments where much of the soil surface lacks vegetation and where bare rock is exposed, most of the rainfall in heavy thunderstorms runs off rapidly and flash floods are common. Yet in dense, humid forests, vegetation and thick, loose soils may absorb water so readily.

Although, alternating wet and dry years have always been observed in tropical rainfall data (Oguntoyinbo, 1978), the declining precipitation effectiveness due to anomalous rainfall patterns since 1972 – 1973 drought suggests that a dangerous trend in mean conditions is taking place (Adefolalu, 1986). This phenomenon has been attributed to the complex interplay of surface temperature anomalies over the tropical Atlantic Ocean and the attendant latitudinal shifts of circulation system during years and human error in permitting the population of both people and livestock to increase to critical levels in many parts of West Africa during wet years (Hastenrath, 1990). This seasonality of West African rainfall as a function of the migratory monsoon as stated by Adefolalu, (1990) results in contrasting summer rainfall patterns. As such, variability in rainfall over different time periods influences water resources planning on daily, monthly, seasonal and annual basis.

Water levels in many parts of the world are getting lower every year. Rivers have retreated from their banks, lakes are shrinking from their former shores and boreholes are pierced even deeper to tap falling water tables (CTA Bulletin, 1995). Over the Bida Basin, the situation is not different. Rainfall (amount, intensity and length of rainy season) and surface runoff (floods and low flows) have fluctuated throughout the period of the study with declining trend. The period of high discharge in the basin coincide with period of rainfall in few large, intense storms resulting in flooding and erosion (Umoh, 1995). This study analyse surface runoff responses to rainfall variability in the study area with a view to identifying key factors that influence surface runoff in the basin.

2.0 The Study Area

The study area is the Bida Basin, Nigeria with areal extent of about 7,540 km^2 covering parts of Gbako, Katcha and Bida Local Government Areas of Niger State, Nigeria (Suleiman, 1998). It is located between latitude 09^0 5' N and longitude 06^0 15'E (Figure 1). The general climate of the study area is the Tropical Monsoon type (Am) characterised by alternate wet and dry season, with rainfall occurring in the rainy season months of May to October. Temperatures are relatively high throughout the year hovering between 27 ^{0}C and 35 ^{0}C.

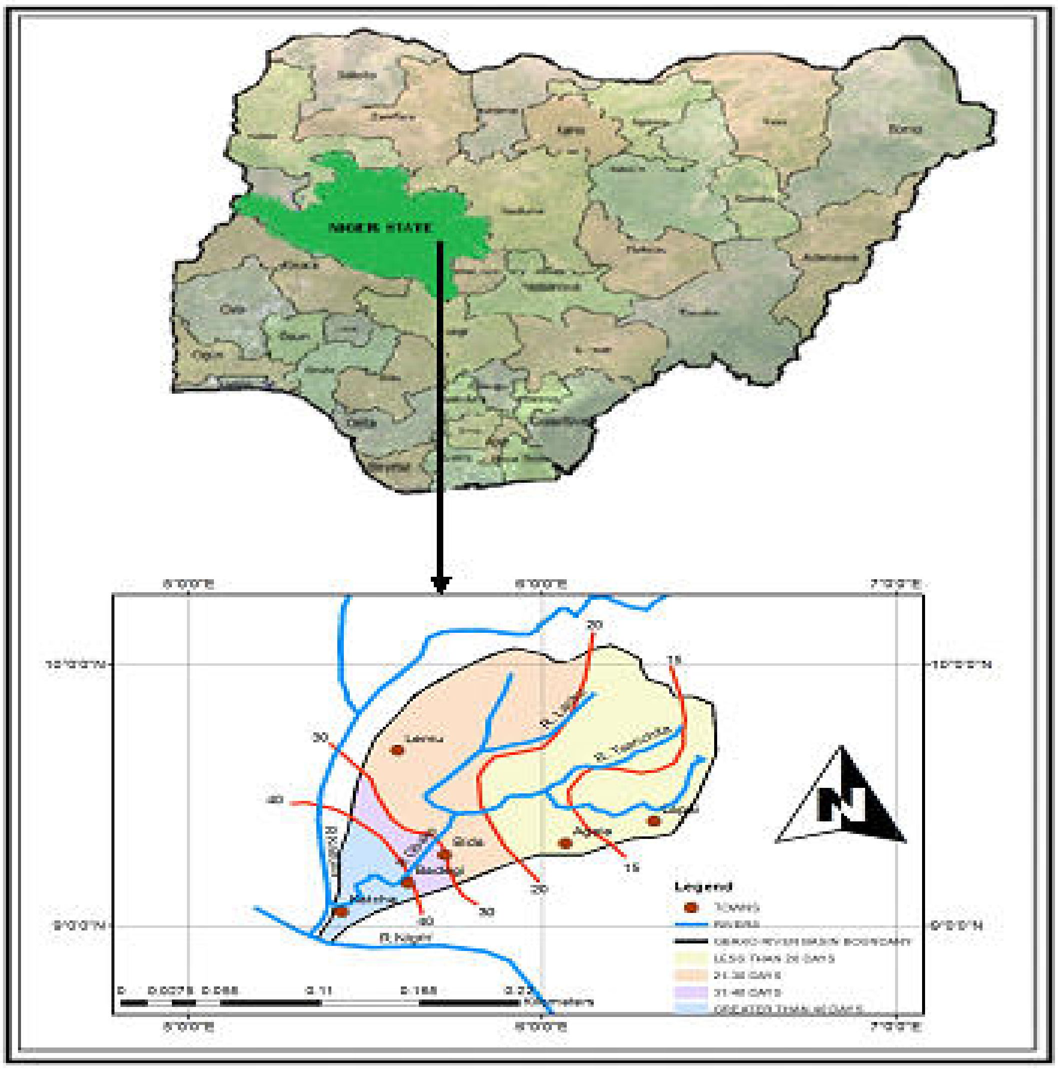

Figure 1: The Bida Basin (The Study Area)

3.0 Materials and Methods

Secondary data were used in this study. Monthly and annual rainfall data for the study area for 30 years (1980-2009) were obtained from the Nigerian Meteorological Service. Both descriptive and inferential statistical methods were used in data analysis and interpretation. The descriptive methods include mean, frequency analysis and graphs.

The calculated mean was done using the formula:

$$X = \frac{\sum^{N} \alpha}{N} \text{ ………………… (1)}$$

Where X is the observed parameter, Σ is the summation symbol and N is the number of observations.

Correlation coefficient was computed to determine the relationship between the variables. The standard deviation (SD) used is the most common measure of variability and it is expressed as:

$$\textbf{SD} = \sum_{i=1}^{n} \left(\frac{x - \bar{x}}{n-1} \right) \text{ ……………………… (2)}$$

Where:

SD = Standard Deviation

$\bar{X}$ = The value of the observed parameter and

$$\textbf{CV} = \frac{SD}{\bar{\bar{X}} -} x \frac{100}{1} \text{ ……………………………. (3)}$$

Where:

X = the daily, monthly or annual variables for a given period.

N = number of cases being considered in the variable.

∑ = span of all the values of variable X e.g reservoir inflow.

In order to standardize the SD for data series, it is divided by the mean value to produce Coefficient of variation, which is a useful measure for comparative purposes where an annual series is normally distributed and where mean totals are not low (Gregory, 1969).

After, the regression analyses of the correlated variables were done to develop regression model. The regression model can be described by the equation that follows:

Y – a x + b …………………………. (4)

Where, X = time (year), a = slope coefficients and b = least square estimates of the intercept. Both the correlation and regression analysis were computed using Microsoft Excel Software Application and the Statistical Package for Social Sciences (SPSS) Version 16.0 for Windows.

Probability Analysis. To determine the probability of occurrence of both rainfall and computed runoff values, the following formula was applied.

$$P(\%) = \frac{m - 0.375}{N + 0.25} \times 100 \text{ ……………………………… (5)}$$

where:

P = probability in % of the observation of the rank m
m = the rank of the observation
N = total number of observations used

The return period T (in years) can easily be derived once the exceedance probability P (%) is known from the equation:

To calculate the recurrence interval (T) according to the Gingerten Plotting formula (Duncan, 2005):

$$T = \frac{n+0.12}{m-0.44} \quad \text{.............................. (6)}$$

Where:

T = recurrence interval
n = total number of years of record used
m = magnitude of rank or order of the annual flood discharges from the greatest (1) to the smallest for the number of years on record.
0.12, 0.44 = constants

4.0 Results and Discussion

Table 1 depicts the rainfall statistics for Bida Basin. Rainfall hovers between 64 mm in April to highest monthly value of 226 mm in September. Variability in rainfall is high in the dry season months of November to March with variations in the range of 92 percent in March to about 184 percent in November. The peak of the wet season months of July, August and September have low variability. Values range between 25 percent and 30 percent. This can be explained by the continuous daily rainfall during these months.

Figure 2 illustrates the monthly distribution of rainfall over the Basin. Rainfall starts in March/April and progressively increases reaching its peak in August/September and thereafter decline until cessation in late October. The Basin enjoys about 7 months of rainfall and 5 months of dry season.

Table 2 shows the annual distribution of rainfall over the Bida Basin. During the 30 year study period, rainfall in the Basin ranges between 900 mm and 1500 mm. The years 1983, 1986, 1996 witnessed low rainfall. These years, according to Suleiman (2013), witnessed drought situation of sort within Basin occasioned by late onset, early cessation of rainfall and hence decreased length of rainy season. The years 1994, 2001, 2006, 2007 had annual values exceeding 1400 mm. The rest years recorded over 1000 mm of rainfall annually.

Table 3 is the ranked annual rainfall values over the Basin. The trend is that the years 1980s witnessed downturn in rainfall amount. Rainfall however, picked up from the 1990s over the Basin with values in the range of 1100 mm and 1300 mm.

Figure 3 is the percentage probability for observed series of annual rainfall totals. The obtained probability of occurrence or exceedance of a rainfall value of specific magnitude indicates that annual rainfall over the Basin with a probability level of 10 percent of exceedance is 1200 mm (See Figure 3). That is on the average; annual rainfall of 1200 mm would be equaled or exceeded during the study period.

Table 1: Annual Rainfall Statistics for the Bida Basin

	Mean monthly Rainfall											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	0	1	14.9	63.6	135.8	166.4	219.8	206.3	226.9	12.6	4.3	0
% of Annual Rainfall	0	1	1.2	5.4	11.6	14.4	18.8	17.7	19.4	10.8	0.3	0
SD(mm)	0	1.3	22.4	40.6	47.8	77.5	68.0	51.8	61.4	36.8	7.9	0
CV. (%)	0	162.5	92.0	58.9	35.2	46.5	30.9	25.1	27.0	29.2	183.7	0

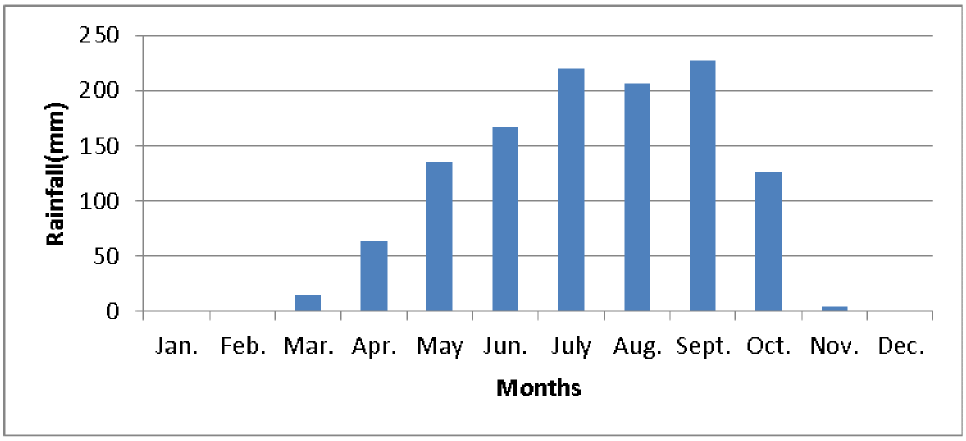

Figure 2: Monthly Rainfall Distribution at the Bida Basin.

Table 2: Annual Rainfall Distribution, Bida Basin (Nigeria)

Years	Annual Rainfall (mm)	Years	Annual Rainfall (mm)	Years	Annual Rainfall (mm)
1980	1117.4	1990	1109.9	2000	1274.5
1981	1031.8	1991	1316.7	2001	1363.9
1982	1182.9	1992	1241.3	2002	1159
1983	981.7	1993	1069.4	2003	1048
1984	1025.8	1994	1412.3	2004	1119.8
1985	1025.8	1995	1279.3	2005	1076.5
1986	966.8	1996	698	2006	1423.2
1987	938.8	1997	876.4	2007	1423.4
1988	1224.3	1998	1237.3	2008	1269.2
1989	977.6	1999	1249.5	2009	1403.3

Table 3: Ranked Annual Rainfall Data, Bida Basin (Nigeria)

Years	R (mm)	m	P (%)	Years	R (mm)	m	P (%)	Years	R (mm)	m	P (%)
2007	1423.4	1	2.07	1992	1241.3	11	35.12	2003	1048	21	68.18
2006	1423.2	2	5.37	1998	1237.3	12	38.43	1981	1031.8	22	71.49
1994	1412.3	3	8.68	1988	1224.3	13	41.74	1984	1025.8	23	74.79
2009	1403.3	4	11.98	1982	1182.9	14	45.04	1985	1025.8	24	78.1
2001	1363.9	5	15.29	2002	1159	15	48.35	1983	981.8	25	81.41
1991	1316.7	6	18.60	2004	1119.8	16	51.65	1989	977.6	26	84.71
1995	1279.3	7	21.9	1980	1117.4	17	54.96	1986	966.8	27	88.02
2000	1274.5	8	25.21	1990	1109.9	18	58.27	1987	938.8	28	91.32
2008	1269.2	9	28.51	2005	1076.5	19	61.57	1997	876.4	29	94.63
1999	1249.5	10	31.82	1993	1069.4	20	64.88	1996	698	30	97.93

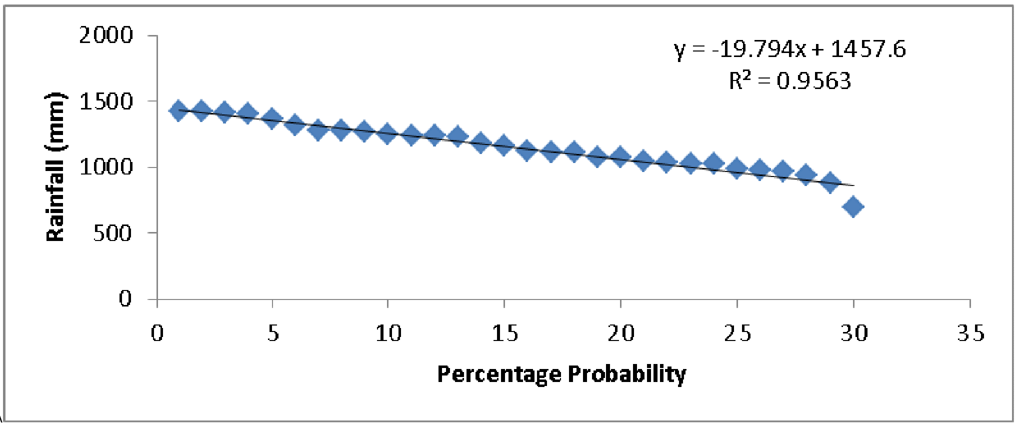

Figure 3: Probability Diagram for Observed Series of Annual Rainfall Totals

Table 4: Mean Monthly Rainfall and Runoff Data, Bida Basin

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Mean
Rainfall (mm)	0	1	14.9	63.6	135.8	166.4	219.8	206.3	226.9	126	4.3	0	**1165.7**
Runoff (m^3/s)	2.7	1.7	1.7	1.7	5.8	20.2	26.4	21.4	29.5	13.4	13.4	2.8	**133.4**
Runoff as % of Rainfall	0.02	0.01	0.4	1.1	7.8	33.6	58	44.1	67.6	10.1	10.1	0.02	**11.4**

Source: Suleiman (1998)

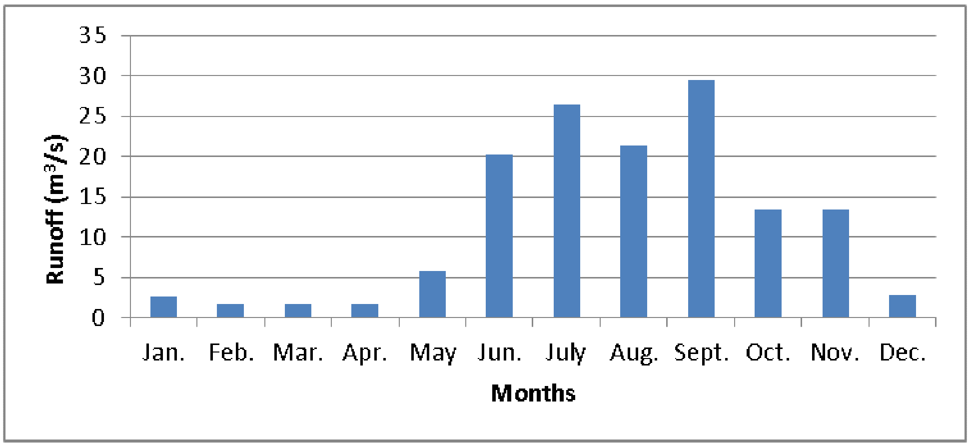

Figure 4: Pattern of Runoff over the Bida Basin (Nigeria)

The Basin enjoys seven months of rainfall; from April to October. The strong seasonality in rainfall is reflected in the runoff particularly in the River flow regime of the Basin. Figure 4 illustrates the runoff pattern over the Basin. The characteristics of the streamflow with high magnitude runoff in the wet season months of May and extending to dry season month of November reflect what obtains in the humid tropics which is the domain of study area. The dry season months of December to May, witness low flows. Base flow from the groundwater recharge largely governs runoff during this period.

The streams in the basin are perennial; that is, flow all the year round with high discharge only during the wet season and this is so because rainfall is identified as the sole generator of runoff in the basin. Therefore, the declining trend in rainfall over the years is reflected in the over all decline in runoff leading to variability in annual flow regime.

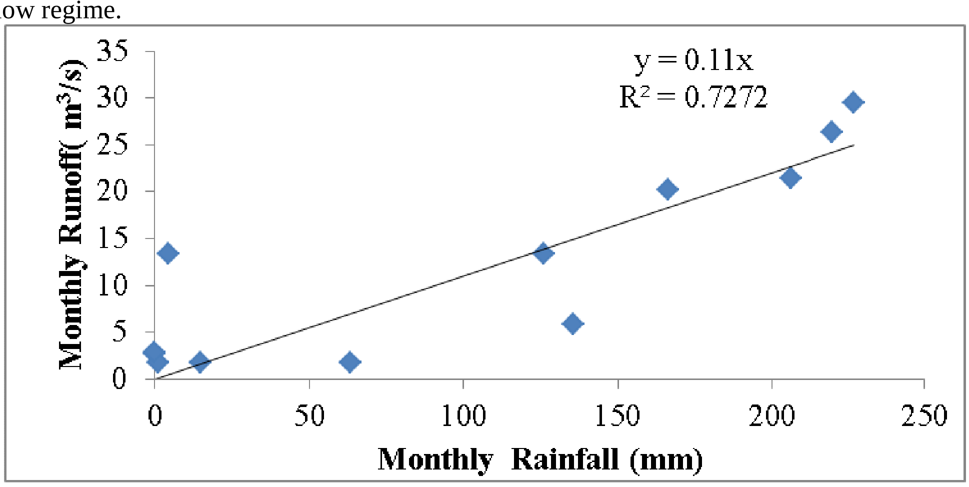

Figure 5: Correlation of Rainfall and Runoff at Bida Basin

Figure 5 illustrates the correlation rainfall and runoff which stood at 0.73 (73 percent) indicating strong linear relationship. This can serve as useful parameter for estimating extreme events either of dangerous floods or of harmful droughts in the Basin. Extreme peak flows result in plain flooding and general flooding particularly between the months of July and September causing localized inundation low lying areas. The period of low flows may also pose a significant water use problem for both domestic and irrigation purposes.

5. Conclusion and Recommendations

One major characteristics of rainfall in this basin is its strong seasonality; alternating between wet and dry months which is also reflected in the runoff pattern over the basin. The period of maximum runoff in the basin coincides with period of high rainfall amounts. Therefore the decline in rainfall at any period in time reflects easily in the overall decline in surface runoff in the basin. Therefore, attention should be focused on development of networking of continuous observation and monitoring of hydrometeorological variables and also control of environmental factors that influence the hydrology of the Bida Basin.

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