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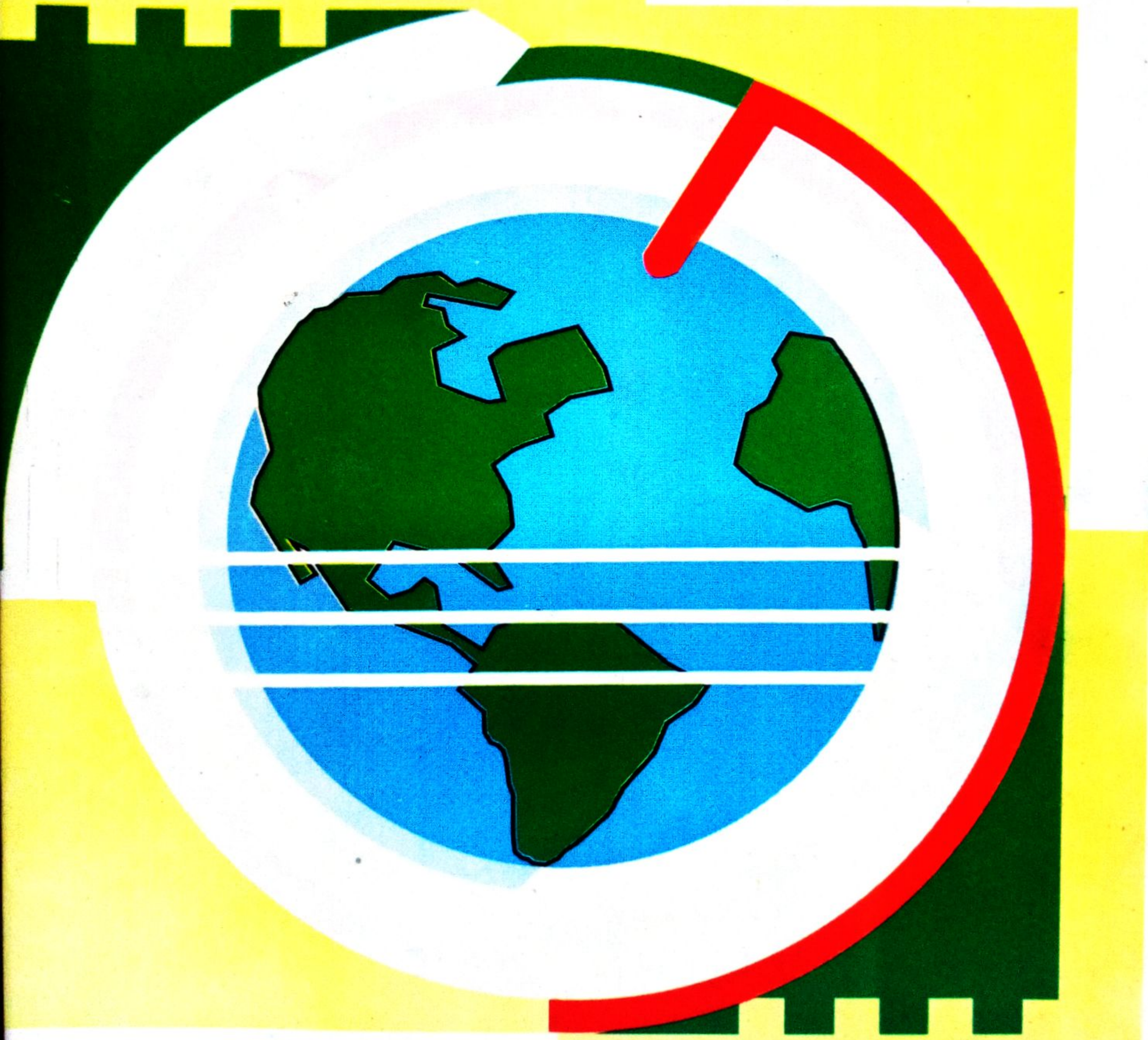

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USING WATER BALANCE APPROACH IN RESERVOIR MANAGEMENT FOR SUSTAINABLE POWER GENERATION AT KAINJI HYDROPOWER DAM, NIGERIA

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Abstract

Understanding the mechanisms of climate variability which is reflected in rainfall on time scale of seasonal to several years is a prerequisite for any prediction and planning of power generation enterprise and also for run-off and flow regime of rivers and streams. The water balance of an area depends on the meteorological factors influencing precipitation and evaporative loss from plants and soils. This paper investigated power generation planning responses to water availability factors at Kainji hydropower dam. The watershed or catchment method where flow characteristics of the catchment basin are related to climatic variables was used. The results show that availability of moisture follows the pattern of rainfall distribution over the basin, which is reflected in the power generation planning responses. It is therefore recommended that careful assessment of water needs for planning purpose and continuous monitoring of various hydrologic variables be made to ensure optimization of water use for sustainable hydropower generation in the study area.

Keywords: Water Balance, Hydropower, Climate, Basin, Rainfall and Watershed

Introduction

Availability of water for all land use activities (agricultural and hydrological) is dependent on steady rainfall during any rainy season, as rainfall characteristics influence the amount and character of available moisture. The water balance studies are modeled to provide a general overview of water conditions in the study area. Water balance techniques, one of the main subjects in hydrology, are a means of solution of important theoretical and practical hydrological problems. On the basis of the water balance approach, it is possible to make a quantitative evaluation of water resources and their change under the influence of man's activities. Sokolov et al (1974) asserted that the study of the water balance structure of lakes, river basins and ground-water basins forms a basis for the hydrological substantiation of projects for the rational use, control and redistribution of water resources in time and space (e.g inter-basin transfers, streamflow control, etc.). Knowledge of the water balance assists the prediction of the consequences of artificial changes in the regime of streams, lakes, and ground-water basins. Current information on the water balance of river and lake basins for short time intervals (season, month, week and day) is used for operational management of reservoirs and for the compilation of hydrological forecasts for water management (Jackson, 1989).

An understanding of the water balance is also extremely important for studies of the hydrological cycle. With water balance data, it is possible to compare individual sources of water in a system, over different periods of time and to establish the degree of their effect on variations in the water regime. Further, the initial analysis used to compute individual water balance components and the coordination of these components in the balance equation makes it possible to identify deficiencies in the distribution of observational stations, and to discover systematic errors of measurements (Gray, 1970). Chapman (1970) stated that water balance studies provide an indirect evaluation of an unknown water balance component from the difference between the known components (e.g. long-term evaporation from a river basin may be computed by the difference between precipitation and runoff).

Toebees (1961) opined that water balance studies are useful for (i) a continuous survey of irrigation requirements; (ii) the prediction of low flow and (iii) an index of the condition of a catchment. Jackson (1989) further enumerated the application of water balance studies to among others, (i) providing the general overview of water conditions in an area; (ii) form part of a model investigating rainfall-runoff relationship and stream flow prediction from climatic data (ii) to assess the suitability of an area for a particular crop; (iii) to assess irrigation requirements both quantity and interval; and (iv) to assess human impact on the system. The seasonality of West African rainfall as a function of the migratory monsoon as stated by Adefolalu (1990) results in contrasting summer rainfall patterns, soil moisture change and drainage. As such, variability in rainfall over different time periods influences water balance and hence agricultural and hydrological planning on daily, monthly, seasonal and annual basis.

This study aimed at providing a climatological guide for effective water utilization for hydropower generation in the dam.

The Study Area

The Study Area is the Kainji Hydro Electric Power Dam located between Latitude 09° 50'N Longitude 10° 55'E on the River Niger at the downstream tip of Kainji Island in Borgu Local Government Area of Niger State, some 402 kilometers North East of Lagos and 605 Km Northwest of Abuja, Nigeria's Capital City. The dam has a surface area of about 1250 km^2, total storage volume of 15 billion m^3 with maximum length of 136 km and dead storage of about 3 billion cubic meters. It is a Federal Government project which was initiated in 1964 and completed in 1968. It was initially managed and operated by Niger Dams Authority (NDA) and later National Electric Power Authority (NEPA) which was established by Decree No 24 of 1st April 1972 with the merger of NDA and ECN to form NEPA now Power Holding Company of Nigeria (PHCN). It is empowered to maintain an efficient, coordinated and economic system of electricity supply to all the nooks and crannies of the Nigeria. Kainji Power Station is thus the forerunner of PHCN's present three hydro-electric power development schemes in Nigeria.

Figure 1: The Kainji Dam Reservoir, Nigeria
Source: www.wikipedia.org/wiki/Kainji Lake (2011)

According to NEDECO and Balfour Beatty (1961), two patterns are discernable in the seasonal hydrological regime of River Niger in Kainji. In the months of May to October rainfall in the Northern parts of Nigeria, South of Niamey produces flood that quickly reaches Kainji area with a peak of 7,000 - 8,000 $m^3 s^{-1}$ in September to October. This flood water is laden with silt and clay sediment and is of high turbidity. Due to its colour, it is locally called 'white flood'. The second flood originates from the rivers headwater region from rivers of high annual rainfall in the Fouta Djallon highlands in Guinea and passes through sub-arid region and deltaic swamps in Timbuktu. In this area, much of the silt is lost to evaporation and infiltration. Little water is added before it reaches Kainji in November with a peak flow of 2000 $m^3 s^{-1}$, the water is relatively clear known as black flood (Oyebande et al, 1990; Mbagwu et al, 2000; Olaosebikan et. al, 2006). These floods lead to high water levels which always give rise to water release at the dam sites and eventually have negative consequences on the downstream communities.

Methodology

This study utilized forty year record (1969-2009) of hydro meteorological data of rainfall, evaporation, temperature and stream flow. The data were used to compute the mean, totals and other derived parameters such as Potential Evapotranspiration (PET), Actual Evapotranspiration (AET), Soil Moisture (SMD) and Readily Available Moisture (RAS) etc.

Both descriptive and inferential statistical methods were used in data 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, □ is the summation symbol and N is the number of observations.

Correlation coefficients of the main meteorological variable (Rainfall) on hydrologic and reservoir variables were computed to determine the strength of the relationship between the variables. 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:

$$Y - a x + b \text{ .... (2)}$$

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.

The watershed or catchment method; where flow characteristics of the basin are related to climatic variables and other environmental factors that affect output to establish a physically based statistically significant relationship with the output is utilised.

Jackson (1989) gave the water-balance equation as:

$$R = Et + \Delta S + \Delta G + Q + L \quad (3)$$

Where:

Et = Evapotranspiration from the catchments (mm)
R = Rainfall (mm)
Q = Stream flow (m^3/sec)
ΔG = Water storage change beyond root range (mm)
L = Out flow/flow other than past stream measurement point.
ΔS = Water storage change within root range (mm)

The areal volume of the water balance parameters were calculated using Warehouse (1977) method of estimating volume of area precipitation which state that for a given area in square kilometers and an annual precipitation in millimeters per year, the volume of total rain will be in km^2 multiplied by mm or m^3 multiply 10^6.

The areal extent of the Kainji Reservoir is 1250 squares kilometers and the annual area volume of the water balance parameters are as follows:

Rainfall	=	16, 022. 5 X 10^6 m^3 per year
Infiltration	=	13, 162. 5 X 10^6 m^3 per year
AET	=	70, 225. 0 X 10^6 m^3 per year
SR	=	17, 000. 0 X 10^6 m^3 per year

Results and Discussion

Table 1 summarizes the water balance distribution at Kainji dam. The maximum PET at Kainji dam is 130 mm in January and lowest, about 48 mm in August. The AET is lowest also in January and correspondingly the maximum AET is 95 mm in November. The annual rainfall total of 1283 mm exceeds the annual computed values of PET, RAS, SR and AET; signifying a positive relationship of moisture availability.

Figure 2 depicts the pattern of water balance distribution over the basin. The SMD is zero for most part of the year and AET and PET vary slightly from January to April of any hydrological year. Figure 3 illustrates the monthly rainfall distribution at Kainji. About 50 percent of monthly rainfall total accumulates on the three heaviest rainy months of July, August and September when values reach up to about 320 mm.

Rainfall generally begins in March/April, increases until the months of September and decreases thereafter until cessation takes place completely in November. The months of November to February are dry. Though, rainfall begins in March/April, the amounts are always very low, less than 50 mm. Three months; July, August, and September together represent the period of highest rainfall in the Kainji dam and consequently significant reservoir inflow harvest.

Figure 4 illustrates the distribution of rainfall and evaporation in the basin. The difference between rainfall and PET defines two seasons in the study area. The Water balance analysis depicts three scenarios: moisture deficit, moisture recharge and moisture surplus resulting in 6 months of moisture surplus and 6 months of moisture deficit. The severity of the dry season increases during the sequence of months with excessive Potential Evapotranspiration. The months of November to April of any hydrological year suffers moisture deficit in the basin. These are dry season months in the basin. About 6 months, May to October are characterized by moisture surpluses. This is the wet season period in the basin (See Figure 5).

Figure 6 shows the seasonal distribution of runoff over the study Area. At Kainji, three periods are critical. The first is August to October when the white flood will be raging. This is derived mainly from the immediate vicinity to the North of lake Kainji in Nigeria. The second period is the period of the Black flood between late November and March of the following year. The third period is the period between April and July when inflow becomes insignificant as black flood enters its recession.

Table 2 shows the correlation analysis between runoff attributes and power generation. Rainfall and runoff have dominant explanation of 83 percent and 78 percent respectively for power generation. This pattern can be explained in respect of the differences in the capacities of the three major dams and their surface areas with Kainji accounting for 15 billion m^3, Shiroro 7 billion m^3 and Jebba 1 billion m^3 (Suleiman, 2013).

Table 1: Average Monthly Water Balance of Niger River at Kainji dam

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
Rainfall (mm)	1	5	17	56	147	176	237	258	276	105	5	0	1283
PET (mm)	130	124	113	104	81	63	59	48	51	72	95	113	1053
R.A.S. (mm)	0	0	0	0	158	180	180	180	180	180	28	15	1201
Infiltration(mm)	0	0	0	0	0	62	117	210	225	33	0	0	647
A.E.T (mm)	1	5	17	56	81	63	59	48	51	72	95	113	562
S.M.D (mm)	129	179	86	48	0	0	0	0	0	0	0	0	392
S.R (mm)	0	0	2	2	0	31	18	48	28	15	2	0	152

Source: Suleiman (2013)

Table 2: Correlation of Selected Reservoir Elements to Power Generation at Kainji Dam

Variable	Power Generated	Rainfall	Inflow	Outflow	Reservoir Elevation
Power Generated (MW/hr)	1.00	0.825**	0.336	0.566	-0.197
Rainfall (mm)		1.00	-0.140	-0.357	0.098
Inflow (m^3/sec)			1.00	0.769**	0.784**
Outflow (m^3/sec)				1.00	-0.562
Reservoir Elevation (m)					1.00

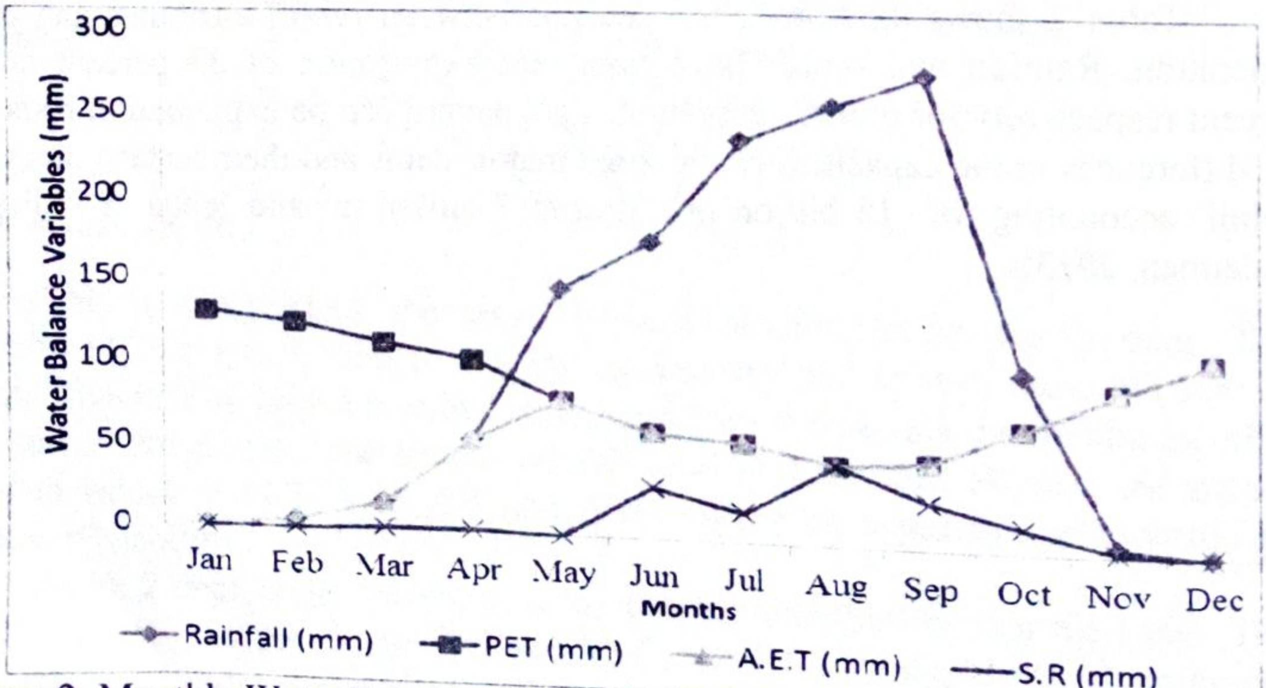
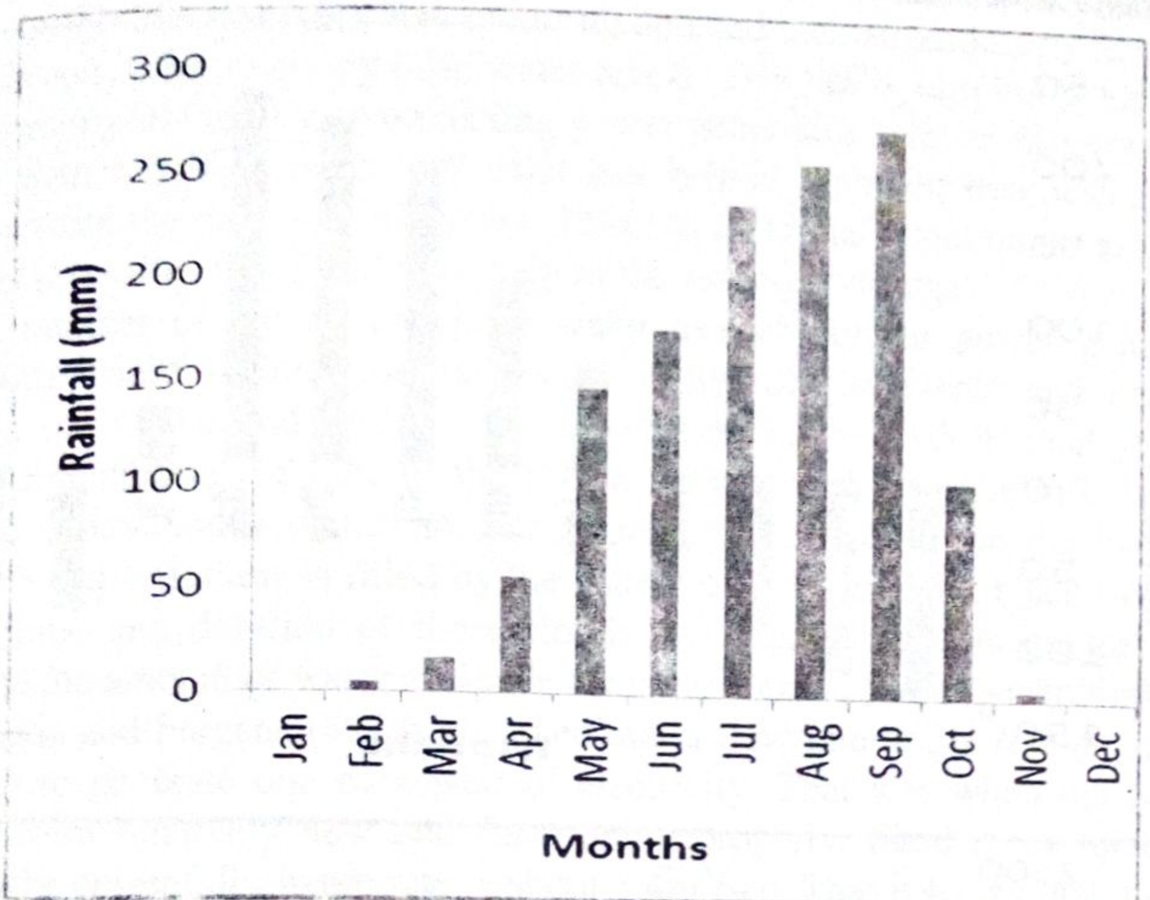


Figure 2: Monthly Water Balance of Niger River Basin at Kainji Reservoir



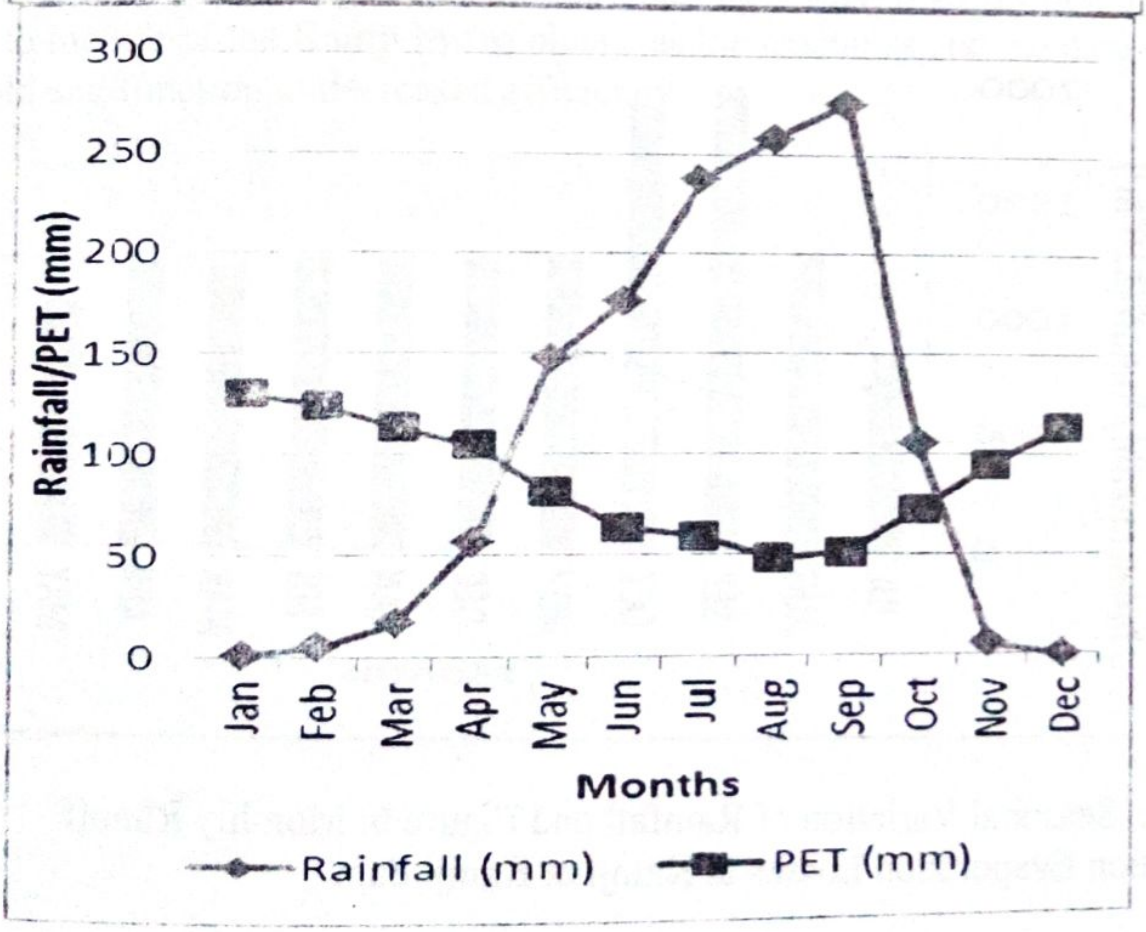
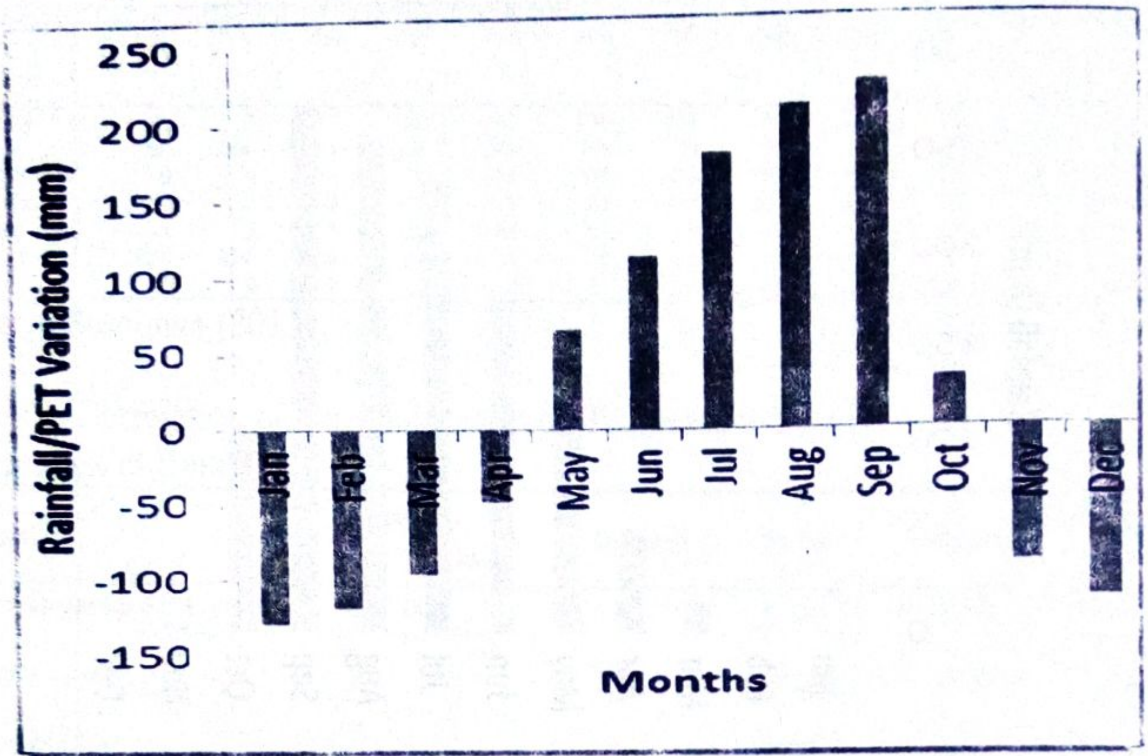


Figure 3: Mean Monthly Rainfall Distribution and Figure 4: Monthly Rainfall/Evaporation at Kainji dam Distribution at Kainji dam



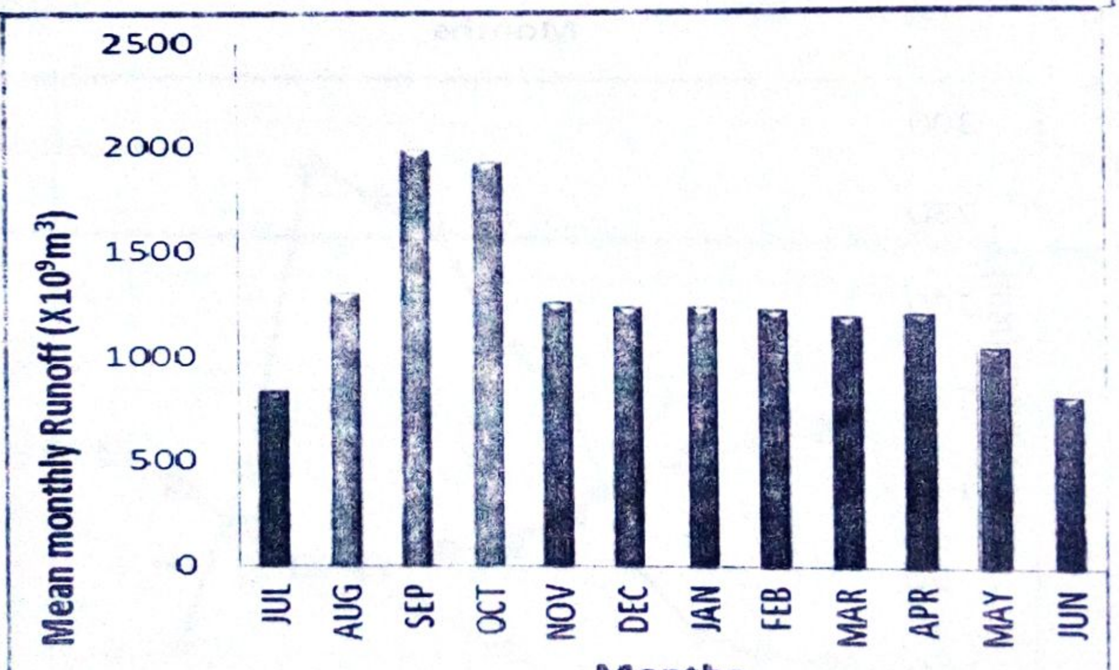


Figure 5: Seasonal Variation of Rainfall and Figure 6: Monthly Runoff Distribution Evaporation Losses at Kainji at Kainji dam

The higher the reservoir level, the more the available water to turn the turbines for continuous power generation. Correspondingly, if the reservoir level is low below the penstocks level, the operation decision is to shut down some turbines to conserve water to keep the power plants running. This usually happens at critical periods especially during the dry season periods when inflow into reservoir is low. At Kainji, because of over 40 years of surface runoff from the upper and middle reaches of the Niger River into the reservoir, lots of silting and sedimentation occupy large portion of the reservoir, thereby giving false water levels. This has in turn not made reservoir level a more useful variable in predicting power generation. However, turbine release at Kainji dam has been propitious as it has helped maintain hydroelectric power generation from the dam over the years. This has insidious effect on the operation of the dam as it resulted in a significant drop in the reservoir storage.

A number of factors influence water availability for power generation at Kainji dam. These include the influence of hydrologic events and engineering projects at the Upper and Middle Niger, variation in the hydrological year which starts in July and ends in June of the following year and thus, the influence of the White and Black floods which are consequent on rainfall within the hydrological year. The Kainji reservoir is filled by the waters of the white and black floods. Both the magnitude and duration of these floods have serious effects on the reservoir storage and the amount of water available for hydroelectric power generation.

Sagua and Fregene (1977) observed that a flow rate of $3m^3$/sec at Kainji dam is required to generate one megawatt of electricity. That was when the generating machines were relatively new and functioning properly. Field measurements now show that the current discharge rate is about $3.4m^3$/sec. That is to say that more water is central to the life of the Kainji hydro plants, as the machines and the dam structures are now old and function at decreased efficiency.

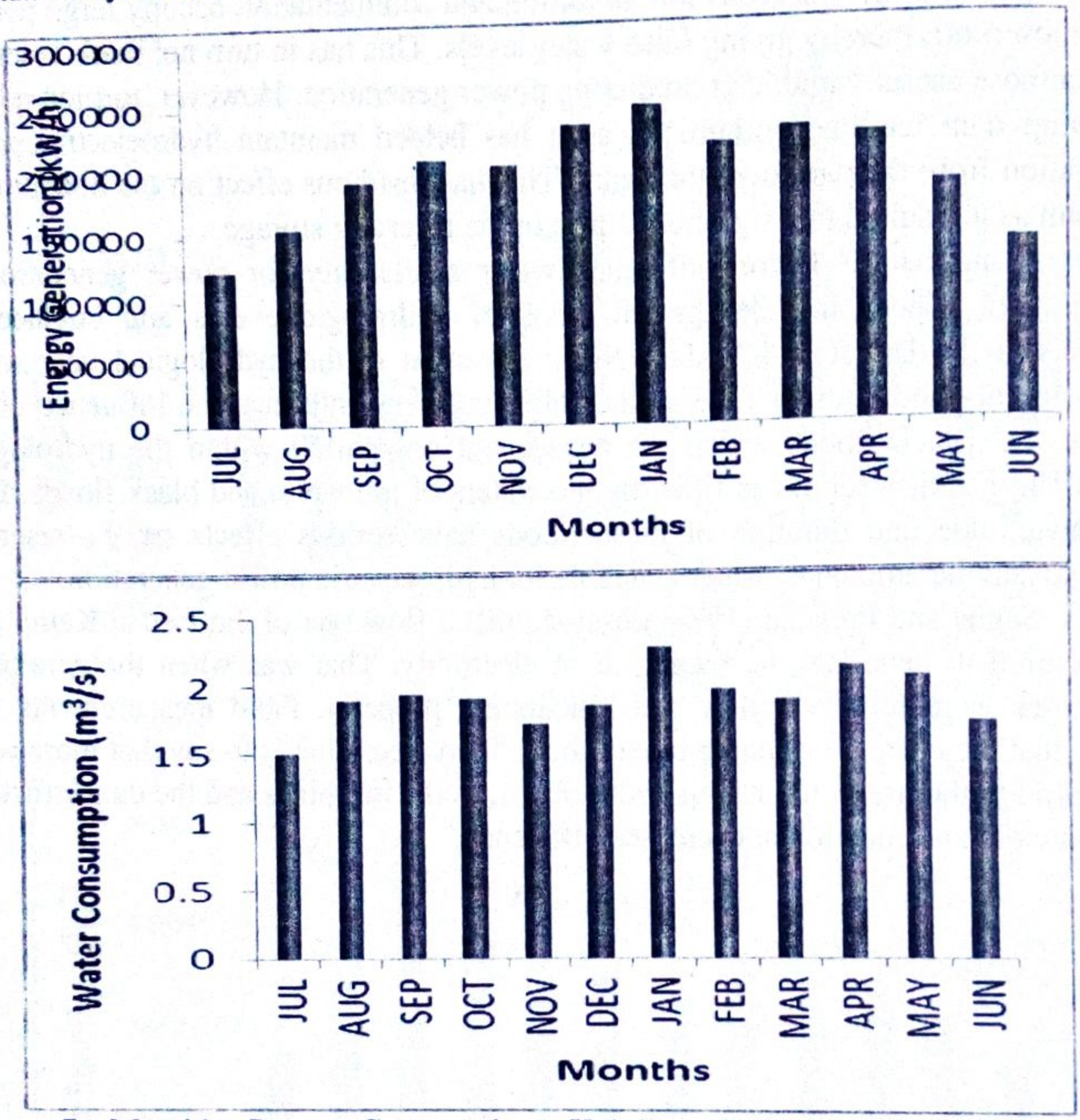


Figure 7: Monthly Power Generated at Kainji and Figure 8: Monthly Water Consumption for Power Generation at Kainji dam

Figure 7 shows the monthly power generated and water consumption at Kainji dam. Analysis of long time power generated on monthly basis reveal that power generation is mostly higher in January to March with generation reaching about 2500 MW/h. Power generation is however, low in the months of April to July as Black flood ceases. To corroborate this, Ajibade (2001) asserted that power system disturbances are common during rainy season and thus forcing power generating machines to be periodically out of service and hence, low power output.

The pattern of monthly water consumption for power generation also corresponds to the pattern of energy generated (See Figure 8). This signifies strong positive relationship between water and power. The month of January record the highest rate of water consumption of over 2 billion cubic meters and followed by the months of April and May. The consumption rates for the month of August, September and October is about 1.8 billion cubic meters. Water release will have to continue every month even if power generation is not achieved. This is because holding too much water that exceeds the dam's carrying capacity could lead to dam collapse and about 85 percent of inflow into Jebba reservoir, some 100 kilometers downstream is from Kainji outflow and so the Jebba reservoir must be fed.

Conclusion and Recommendations

In any meaningful assessment of water needs for planning, the application of knowledge of water balance studies is desirable as this gives an insight into hydrologic planning purposes. The distribution of moisture in the study area on seasonal, monthly and annual basis identifies periods of moisture availability and moisture deficits as it relates to hydropower generation. It is therefore recommended that careful assessment of water needs for planning purpose and continuous monitoring of various hydrologic variables be made to ensure optimization of water use for sustainable hydropower generation in the study area.

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