Teleconnections of seasonal reservoir inflow with ENSO indices: Application to Kainji Hydropower generation Reservoir in Nigeria

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Abstract: This paper presents application of climate information to the prediction of seasonal reservoir inflow for Kainji hydropower generation dam in Nigeria. The direct linkage between Oct-Nov-Dec (OND) seasonal stream flows and Sea Surface Temperature (SST) of the preceding Jul-Aug-Sept (JAS) season extracted from Atlantic and ENSO index (NINO3) in the NOAA's climate diagnostic center's interactive plotting and analysis tool were identified by performing diagnostic analysis using lag-3 correlation. It was observed that the correlation between reservoir inflow and Atlantic Ocean SST is -0.40, and for ENSO index (NINO3) about -0.60. Negative correlation implies that positive increase in SST anomalies lead to decrease in stream flow. Once the linkages has been established, the predictor variable, (SST anomalies) were selected from the KAPLAN data bank for different regions of significant correlation, which include US coast, North Atlantic, South Atlantic and ENSO index (NINO3) and the historical reservoir inflow data is loaded inside SANKA data bank located inside International Research Institute (IRI) data library. The correlation and composite analysis were conducted to construct the model for seasonal climate forecasting of the reservoir inflow for Kainji reservoir using the CDC web based analytical tool known as climate predictability tool (CPT). The highest correlation of the observed reservoir inflow at Kainji with the predictor variables is -0.50, while the highest correlation between the observed and predicted reservoir inflows was obtained as 0.70. This implies that with climate base information, long lead reservoir inflow can be predicted and used to plan for future energy generation.

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Introduction

Water managers throughout the world are facing the increasing problem of meeting demands for a wide variety of purposes including municipal, industrial, agricultural, power production, and environmental needs. Much work has involved studying climate phenomena such as El Nino Southern Oscillation (ENSO) and La Nino and their impacts on hydrologic variables such as precipitation, temperature and stream flow. Climatologists developed indices based on sea surface temperature, SST and the climate indices are taken as area averages of the regions of highest correlation. In order to utilize climate information to forecast stream flow in a specific basin, it is required to analyze the direct linkages between climate features and stream flow or precipitation in the given basin. The analysis of the linkages was achieved with climate diagnostics techniques developed by climate diagnostic center (CDC), with website (**http://www.cdc.noaa.gov**). Once the linkage is established, the correlation and composite analyses was conducted using the CDC web based analysis tool (Non-parametric stochastic forecasting techniques) known as climate predictability tool (CPT). The climate predictability tool provides a window package for performing functions such as seasonal climate forecast model, model validation, principal component regression and canonical correlation analysis. In this study principal component regression is used to construct the model for seasonal climate forecasting of the reservoir inflow for Kainji reservoir. The model operates on the premise that the statistics (mean, standard deviation, lag (1) correlation, and skew) of the historical flow are likely to occur in the future.

Grantz (2003) reported that researchers have gathered an increasing body of evidence to demonstrate the relationship between large-scale climate features and hydro climatology in the western United States. Much of the work has involved studying climate phenomena such as El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) and their impacts on hydrologic variables (precipitation, temperature and stream flows) in the Western United States. Chiew and McMahon (2002) investigate the global ENSO runoff teleconnections using data from 581 catchments. The consistency and strength of ENSO- stream flow teleconnection across geographical regions was identified. The lag correlation between stream flow and indicators of ENSO and the serial correlation in stream flow are computed to provide a direct indication of the potential of forecasting stream flow several months a head.

There is increasing number of studies investigating the relationship between stream flow and ENSO, but practically all these concentrate on particular countries or regions. Nevertheless, a study by Dettinger et al. (2000) presents multiscale stream flow variability associated with ENSO based on the analyses of stream flow data from over 700 stations worldwide. It is likely that the stream flow-ENSO relationship is stronger than the rainfall-ENSO relationship because the variability in rainfall is enhanced in runoff and because stream flow integrates information spatially (Chiew et al, 1998). Seasonal forecasts of stream flow can benefit the management of water resources, in particular allowing decisions on water allocation for irrigation and environmental flows to be more realistically based (Chiew et al., 1999). Piechota and Dracup (1999) developed long range stream flow forecasting for Columbia River basin, based on El Nino-Southern Oscillation indicators and the understanding that a significant lag relationship exists between El Nino-Southern Oscillation and stream flow. The forecast model was used for long lead forecasts coming 3 -7 months in advance of spring – summer runoff in the Columbia River basin. It was concluded that the study bridges the sciences of climatology and hydrology, thus proposes the practical integration of atmospheric / oceanic information into long – range stream flow forecasting. Piechota et al (2001) developed exceedence probability for stream flow forecast; the development takes persistence of ENSO indicator and several Pacific / Indian Ocean sea surface temperature (SST) series as the main predictor variables. A linear discriminant technique is used to express the forecast as probability of exceedence of continuous stream flow amounts. The forecast model is applied to five Australian catchments for design and operation. Bhuiyan et al., (2006) developed long-term flood forecasting model for the Brahmaputra – Jamuna river in Bangladash based on El Nino Southern Oscillation (ENSO). The research explores the nature and strength of possible teleconnections between the river flow and ENSO variability over the equatorial Pacific Ocean. The research demonstrates relationship between natural variability of average flood flows of July-August-September (JAS) months of the Brahmaputra-Jamuna River and the ENSO index of the corresponding month. Sea surface temperature (SST) of the equatorial Pacific Ocean has been used as ENSO index. The outcome of their research revealed that frequency distribution shows that during El Nino year (warm ENSO) the probability of exceeding the average JAS flow is only around 25%, while during La Nina year (cold ENSO) this probability rises to about 77%. The correlation analysis also shows that the JAS SST of Nino four regions have significant influence on the average JAS flow of Brahmaputa-Jamuna. Discriminant analysis also supports high-flood with La Nina and low-flood with El Nina. The possibility of long-lead forecasting is also evaluated, while the forecast skill of the model depended on the accuracy of SST prediction. Hamlet et al (2002) presented the economic value of the increased hydropower production in the Columbia River Basin as a result of incorporating climate information in the stream flow forecast to increase lead time i.e. six months earlier.

However, there has been little or no research on diagnosing and predicting the variability of stream flows in the middle Niger River Basin, Nigeria. Based on lack of evidence for the existence of any climate base information forecasting techniques / research and the importance of water resources planning in the basin, there is a need to systematically diagnose the stream flow variability in an effort to improve forecasting. In this study, relationships between (Oct-Nov-Dec) stream flows and climate variables from the preceding (Jul-Aug-Sept) are identified and the seasonal reservoir prediction is established.

2. Material and Methods

Kainji Lake is a reservoir on the River Niger in Nigeria. It is formed by Kainji dam which was built between 1964 and 1968. The reservoir is located on latitude 10^o 08’ N and longitude 4^o 37’ E. It is an earth dam with a 66 m high concrete centre structure housing the hydroelectric turbines. The Kainji reservoir is about 135 km long and about 30 km across at its widest point with a surface area of 1,250 km^2. It is capable of storing 15.5 x 10^9 m^3 water of which 92 percent can be drawn down for power generation. The lake submerged the Bussa Rapids, where the explorer Mungo Park lost his life in 1806. Some 44,000 people had to be resettled. Alayande and Bamgboye (2003) revealed that an average daily discharge of 2280 m^3/sec is required to sustain full generating capacity of 760 MW (3 m^3/sec per unit mega watt of electricity). Kainji dam and the reservoir is presented in Figure 1

Figure 1. Kainji dam and Lake

2.1 Data and its space-time

The following data sets for the 1970 – 2003 periods are used in the analysis

(i) Monthly observed reservoir inflow data from Kainji gauging station is loaded into Sankar expert home in IRI data library. Website: http://iridl.ldeo.columbia.edu/expert/home/.sankar/.kainji/.Flow/

(ii) Monthly values of Ocean atmospheric variable SST anomalies, obtained from KAPLAN EXTENDED expert home in IRI data library. Website: http://iridl.ldeo.columbia.edu/SOURCES/.KAPLAN/.EXTENDED/.v2/.ssta/

2.2 Seasonal stream flow model

The seasonality plot is a plot between each month and its respective monthly average reservoir inflow. The monthly plot is presented in Figure 2, there are four seasons of three month each, and their percentage contribution to the mean annual (long-term) is presented in Table 1. Oct-Nov-Dec (OND) season is selected for analysis.

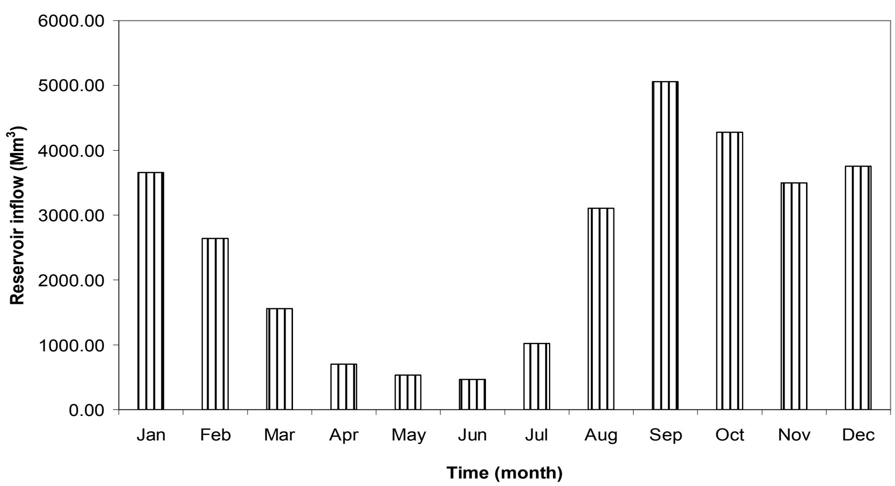

Figure 2 Mean monthly reservoir inflow for Kainji dam along Niger River, Nigeria

Table 1. Percentage contribution by each of the four seasons

Seasons	Amount contribution (Mm^3)	Percentage (%)
Jan-Mar (JFM) season	7856.17	25.95
Apr-Jun (AMJ) season	1700.60	5.62
Jul-Sep (JAS) season	9183.75	30.34
Oct-Dec (OND) season	11528.88	38.09
Annual total	30269.40	100.00

2.3 Diagnostic analysis

Through climate diagnostics, the influence of large-scale climate features on stream flow in the middle Niger River in Nigeria was analyzed. The primary purpose for performing these climate diagnostics is to gather information regarding the physical mechanisms that drive OND seasonal stream flow in the basin as well as to establish predictors that can be used in a forecasting model.

Diagnostic analysis was performed using lag-3 correlation in order to understand the linkages between Atlantic and ENSO indices (NINO3) and the stream flow. The NOAA's climate diagnostic center's interactive plotting and analysis tool was adopted. The websites are http://www.cdc.noaa.gov/Correlation/Custom.html and http://www.cdc.noaa.gov/Correlation/

The correlation plot between 3-months lag SST (JAS season) and stream flow during OND season is presented in Figure 3.

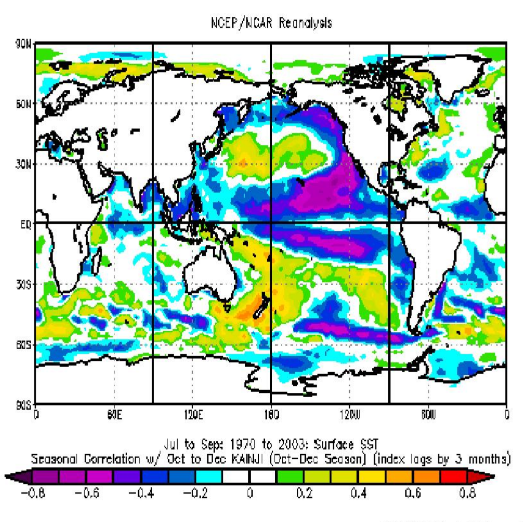

Figure 3. Niger River Lag-3 Correlation for OND season at Kainji gauge site

2.4 Seasonal forecasting model

In seasonal forecasting model the IRI data library and Climate Predictability Tool (CPT) were adopted. The websites are: IRI data library: http://iridl.ldeo.columbia.edu/index.html and CPT: http://iridl.ldeo.columbia.edu/outreach/software/. The predictor variable, which is Sea Surface Temperature anomalies (SSTa) was selected from the KAPLAN data bank for different regions of significant correlation, which include [(US coast, 75W-60W;30N-40N), (North Atlantic, 50W-10W;20N-55N), (South Atlantic, 32.5W-27.5W:20S-5S) and (NINO3, 150W-90W;5S-5N)] while the historical stream flow data is loaded inside Sankar data bank located in IRI data library. The selected predictor variable (SSTa) for OND seasonal stream flow requires JAS seasonal SSTa. The average over the three months in the season for each year is determined and the SSTa data grid was sifted 3 months upward in order to be at the same level with stream flow for correlation analysis. The correlation is carried out and maskrange based on the significant level ($\pm 1.96 / \sqrt{N}$). This was performed in the expert mode of the stream flow. The SSTa (predictor) selected was saved in the CPT data file and Principal Components Regression (PCR) analysis is performed. In order to establish predictor of high correlation, the preceding seasonal stream flow are included as predictor variables i.e. the seasonal stream flow is expressed as a function of preceding SSTa and stream flow as presented in equations 1 to 3.

$$Q_{OND} = \int (SST_{aJAS}) \tag{1}$$

$$Q_{OND} = \int (SST_{aJAS} \; ; \; Q_{JAS}) \tag{2}$$

$$Q_{OND} = \int (SST_{aJAS} \; ; Q_J ; Q_A ; Q_S) \tag{3}$$

Table 2. Statistics of the Models (Leave one out Validation)

Predictors	Pearson correlation between observed and predicted reservoir flow	Root Mean Square Error (RMSE)	Mean Absolute Error (MAE)	Predictor and stream flow Correlation
$SSTa_{JAS}$	0.62	557.80	452.93	-0.41
$SSTa_{JAS}$; Q_{JAS}	0.69	511.06	391.78	-0.46
$SSTa_{JAS}$; Q_J; Q_A; Q_S	0.70	512.42	393.83	-0.50

The results of the statistics of the models were presented in Table 2, while, the relationship between the observed seasonal reservoir inflow with the predictors are illustrated in Figures 4 to 6 and finally the relationship between the predicted and the observed seasonal stream flows are presented in Figure 7 to 9 for various combinations of predictor variables.

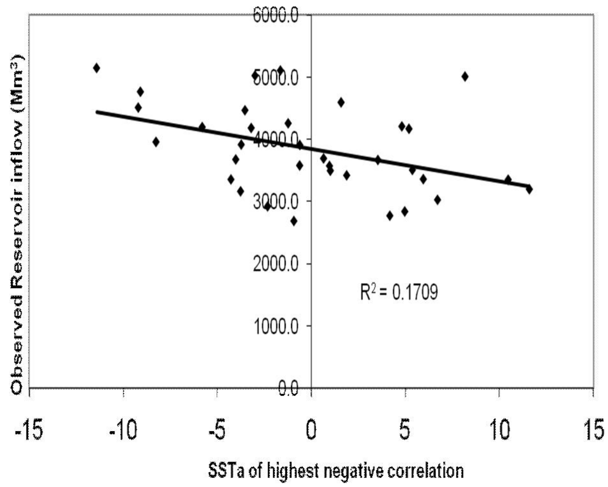

Figure 4. Observed Reservoir inflow with SSTa of highest negative correlation (SSTa only)

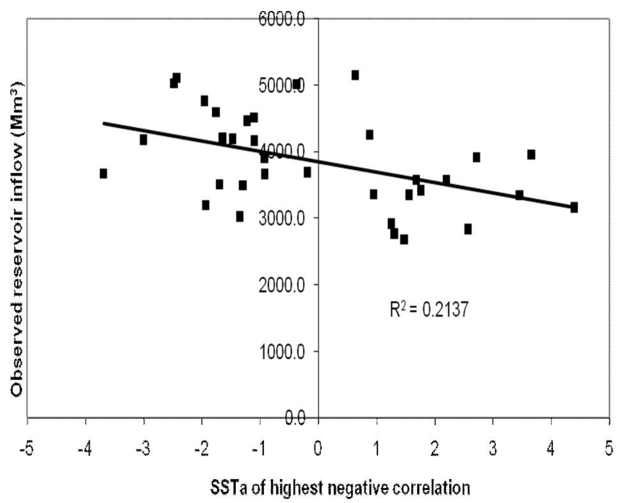

Figure 5. Observed reservoir inflow with SSTa of highest negative correlation (SSTa ; QJAS)

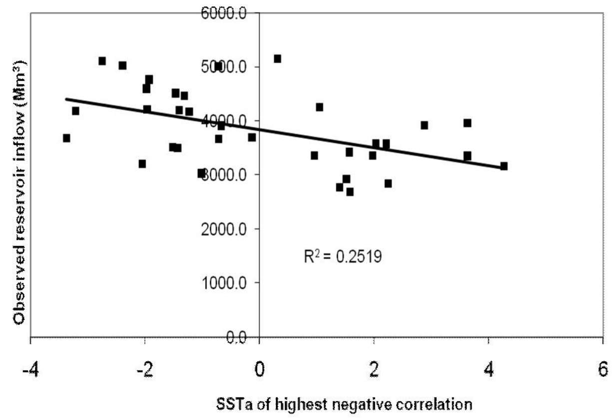

Figure 6. Observed reservoir inflow with SSTa of highest negative correlation (SSTa ; Q_J;Q_A;Q_S)

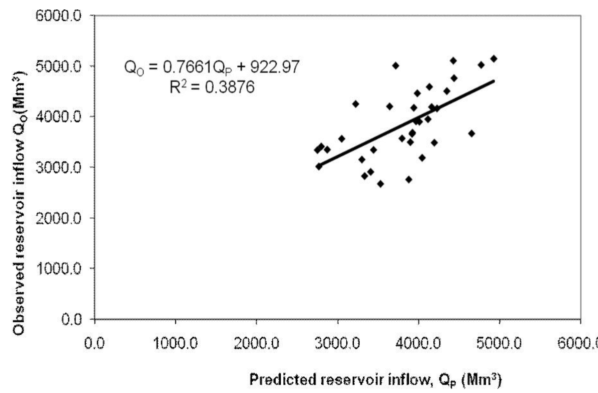

Figure 7. Relationship between observe and predicted OND seasonal flow with SSTa as predictor

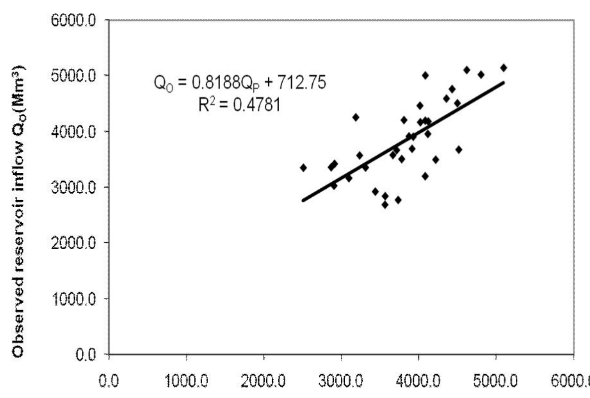

Figure 8. Relationship between observe and predicted OND seasonal flow with preceding flow (Q_{JAS}) and SSTa as predictor

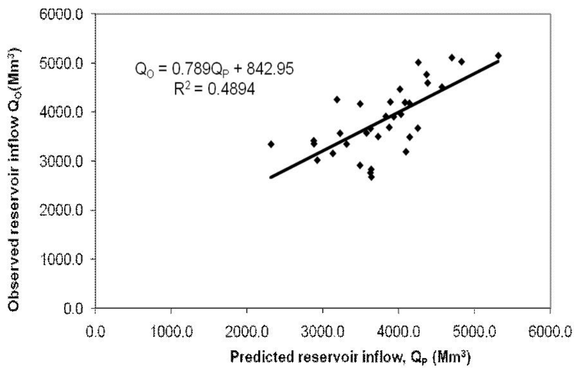

Figure 9. Relationship between observe and predicted ONDseasonal flow with preceding season flows (Q_J, Q_A, Q_S) and SSTa as predictors

3. Results and Discussion

The monthly reservoir inflow data was obtained for a period of 34 years (1970 – 2003) from Kainji hydropower station. Four seasons of three months duration was established for the average reservoir inflow and their percentage contribution to the mean annual flow were estimated as presented in Table 1. The amount contributed to annual mean flow during JFM, AMJ, JAS and OND seasons are 7856.17 Mm^3, 1700.60 Mm^3, 9183.75 Mm^3 and 11528.88 Mm^3 respectively. These constitutes to about 26.0%, 6.0%, 30% and 38.0% respectively. In addition, the average contribution of reservoir flow by each month is presented in Figure 2.

It is important to point out that there has been little or no research on diagnosing the relationship of climate variable with reservoir inflow to Kainji Lake located on Niger River, Nigeria. This study has attempted to establish the linkage between the Kainji reservoir inflow and the predictor variable such as SST anomalies. In establishing the linkages, the reservoir inflow of OND season and climate variable (SSTa) of the preceding JAS season extracted from Atlantic and ENSO index NINO3 were analyzed with NOAA's climate diagnostic center's interactive plotting and analytical tool developed by Climate Diagnostic Center (CDC) with website http://www.cdc.noaa.gov. The correlation plot map obtained is presented in Figure 3 and can be deduced that the correlation between reservoir inflow and Atlantic Ocean SSTa is -0.40, while the correlation between ENSO index (NINO3) and reservoir inflow is -0.60. Negative correlation implies that above normal SST will result in below normal stream flow, i.e positive increase in SST anomalies lead to decrease in stream flow. Whereas positive correlation mean above normal SST results in above normal stream flow, i.e increase SST anomalies lead to increase in the stream flow. Therefore, long term seasonal climate forecast can be obtained from the lag-3 correlation between stream flow and SSTa.

Having established the linkages between the two variables, the seasonal forecasting of Kainji reservoir inflow under climate information using IRI data library and Climate Predictability Tool (CPT) was conducted. The results of the statistics of the models are presented in Table 2. The table revealed that the correlation between predictor and reservoir inflow ranges from -0.41 to -0.50, while the Pearson correlation between the predicted and observed reservoir inflow ranges from 0.62 to 0.70. The relationship between the observed seasonal reservoir inflow with the predictors are illustrated in Figures 4 to 6, while the relationship between the predicted and the observed seasonal stream flows are presented in Figures 7 to 9 for various combination of predictor variables. From figures 4 to 6, it could be observed that the reservoir inflow and SSTa has inverse relationship, that is, the higher the SSTa, the lower the reservoir inflow and the lower the SSTa, the higher will be the value of the reservoir inflow. Similarly from figures 7 to 8, it could be observed that the reservoir inflow and SSTa has direct relationship, that is, the higher the SSTa, the higher the reservoir inflow and the lower the SSTa, the lower will be the value of the reservoir inflow. The relationship in figure 9 gives highest value of coefficient of determination (R^2 = 0.49) between the observed and predicted reservoir inflow, the implication of this is that the model performed better when individual preceding monthly flows are incorporated as predictor.

4. Conclusion

In conclusion the following points are itemized

- The analysis enables the application of climatic diagnosing and prediction tools to study the variability of stream flows at Kainji H.P reservoir situated on Niger river, Nigeria.
- Forecasting models that utilize atmospheric circulation data are useful for basin where hydro-climatic observations are scarce and where flows and other hydro-climatic variables are not strongly auto-correlated. i.e Kainji stream flow and rainfall.
- Incorporating large-scale climate information in a forecasting model can produce more skillful, longer lead-time forecasts. This can produce reliable forecasting and thus improve water resources operations and planning in Niger River Basin.

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