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INFLOW FORECASTING FOR KAINJI DAM USING TIME SERIES MODEL

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ABSTRACT

A time series model of the inflow for a major river is formulated and an exponential smoothening Technique (EST) is developed in this work. The EST is a physically based method which can be devised in such a manner as to emphasize important and dominant features of a process and used to produce a model suitable for specific needs. Forecasts based on this technique can provide very useful results for the short-term and out perform more complex Box and Jenkins models with the added advantage of simplicity and model parsimony. The technique is applied in this paper to develop a non-causal representation of the inflows into the Kainji dam located in the west of central Nigeria on the river Niger. Inflow data from 1992 through 2008 were used to validate the models and provide short term forecasts. The results exhibit good prediction for periods of 6 months, which can be used to refine reservoir management. Longer term models require the ARIMA format in order to fully reflect seasonal and stochastic components.

Keywords: *Exponential Smoothening Technique (ESM), Time Series Model (TSM), Prediction, Forecasting, Filter, Inflow*

INTRODUCTION:

Many of the activities associated with the planning and operation of the components of a water resource system require forecasts of future events. The dam inflow is the most important data for reservoir operation. The condition for forecasting and predicting can result in considerable uncertainty in the hydrologic information that is available. Furthermore, the non-linear relationships between input variables (precipitation, dam inflow, etc.) and output variables (dam inflow, etc.) require more complicated attempts to forecast dam inflow events.

Since Ripple (1883) proposed the schematic determination technique for reservoir capacity in order to forecast the future runoff by using historical runoff data, many hydrologists have studied the rainfall-runoff process and applied forecasting techniques based on statistical methods.

Thomas and Fiering (1962) used AutoRegressive (AR) model, to simulate and generate a runoff series by treating the hydrological data as a time series which has random components. Matalas (1967) and Vicens et al. (1975) extended AR model to ARMA (AutoRegressive Moving Average) model, O'Connell (1974) developed ARIMA (AutoRegressive Integrated Moving Average), Matalas and Wallis (1971) used FGN (Fractional Gaussian noise) model, Weiss (1973) used shot noise model, and Mejia et al. (1974) used broken-line model to forecast runoff series. Eagleson et al. (1966),

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Amorocho (1967) developed linear, nonlinear Transfer Function (TF), respectively. Box and Jenkins (1970) represented the dynamic system to the input-output system by developing TFN (Transfer Function Noise) model. Hannan (1970), Newbold (1979, 1981), and Priesly (1981) studied ARMAX model, which has exogenous terms and similarity with a kind of TF models. Hsu and Adamowski (1981), Anselmo and Ubertini (1979), and Baracos et al. (1981) applied TF model and TFN model to the forecasting of a water resources problem. Awwad (1991) studied streamflow forecasting for large-scale hydrologic systems.

Most of these models require parameters estimates that are rigorous and are accurate for long-term predictions. However, power generation requires daily forecasts which must be simple but accurate in estimation. This is why the exponential smoothening is desirable over the other models.

The Kainji Dam:

The Kainji Dam, a multipurpose project intended for power production, improved navigation of the river, flood control in the Niger Valley and fishery production of over 10 000 tons annually was constructed between February 1964 and August 1968. It sits astride the river Niger in the west of Central Nigeria. The route of the River Niger and the site of the Kainji Dam is shown in Figure 1.

Figure 1: Map of West Africa Showing River Niger Route

The river Niger is the third longest river in Africa, after Nile and the Congo / Zaire Rivers, 4100km long, and It traverses two humid catchments separated by a wide expanse of semi-arid environment. From its source in the Fouta Djallon Mountains of Guinea, it traverses three other countries including Mali, Niger and finally Nigeria where it finally enters the Atlantic Ocean through its delta in the Gulf of Guinea (Alayande and Bamigboye, 2003).

Balfour Beatty & NEDECO (1961), the joint consultants for the dam project, described the seasonal hydrology of River Niger as having two distinct peaks. Rainfall usually occurring in the months of May to October in the northern parts of Nigeria, south of Niamey, produces floods that quickly reach Kainji. This produces floodwaters typically with a peak flow of between 4,000 to 6,000 m^3-s^{-1} occurring sometime in September or October. It is laden with silt/clay sediments and hence has high turbidity that gives its color, which is locally referred to as the "White Flood".

A second flood originating from the river's headwater region of high annual rainfall in the Fouta Djallon highlands in Guinea passes through the sub-arid region and deltaic swamps around Timbuktu. In these areas it loses much of its silt load and water to evaporation and infiltration while very little water is added to the flow before it reaches Kainji in November with a peak flow of about 2,000 m^3 s^{-1}. The water arriving at the Kainji is relatively clear due to its low silt load and is thus locally known as the "Black Flood"

The main purpose of the dam was to provide a cheap, reliable source of power that still provides the base load for the national grid. The result was initially impressive and met the aspirations of the designers. Following the sahelian draught in the third quarter of the twentieth century, there has been a move to establish other dams on the Niger River especially in the semi-arid areas between its headwaters and Nigeria. Presently, the Niger Republic is in the process of constructing a multi-purpose dam on at Kandaji. This is in addition to the Fomi dam in Guinea, Mekrou dam in Benin Republic and Tossaye dam in Mali.

All these in addition to climate change impacts; desertification and water diversion activities for irrigation purposes by peasant farmers along the river course are pointers to an impending reduction of inflow into Kainji reservoir. Intensified use or diversion of water for other purposes in the Sokoto-Rima basin can also reduce the white flood into the Kainji Lake so that the power generating potential of the Kainji power station may be greatly reduced in the near future. The combined effect of all these possible modifications make it essential to develop a reliable and accurate forecast framework for decision making especially for power generation This paper presents an effort to forecast the inflows based on available data using methodology outlined below.

Time Series Model:

Because of the complex and not fully defined relationships between all the variables contributing inflow of a dam, a model is developed which exhibits the same essential characteristics as the process under study, without attempting to identify the causal nature of the relationships between the various relevant interacting variables.

The dynamics of many physical systems can be expressed in terms of a differential equation of the form (1) *especially when various approximations are made to reduce complexity related to linearity and other issue.*

$$(1 + c_1 D + c_2 D^2 + \cdots)Y = (1 + d_1 D + d_2 D^2 + \cdots)X \tag{1}$$

where Y is the output variable,

X is the input variable,

D is the differential operator, and the c_k and d_n are constants where k and n (both integers)are the indices.

Such structurally simple models can often describe complex systems adequately, even when the true nature of the system is not understood.

In the discrete-time case when observations are taken at equally spaced intervals, the above differential equation evolves into a difference form as (2)

$$(1 + c_1 + c_2 \nabla^2 + \cdots)Y_t = (1 + d_1 + d_2 \nabla^2 + \cdots)X_t \tag{2}$$

where

∇ denotes the backward difference operator, defined by $\nabla = Y_t - Y_{t-1}$

Similarly, the complex stochastic behavior of a random process {zt} can often be successfully described in terms of a difference equation relating {zt} to a much simpler random process – a "white noise" process, {at}, having zero mean, constant variance, and no correlation among its members. In that case the system behavior may be expressed as follows:

$$(1 + c_1 + c_2 \nabla^2 + \cdots)z_t = (1 + d_1 + d_2 \nabla^2 + \cdots)a_t \tag{3}$$

Assuming a finite number of constants c_k and d_m, a more convenient form of equation (3) can be obtained by introducing the backward shift operator B,

where

$Bz_t = z_{t-1}$, and $B = 1 - \nabla$:

$$(1 - \phi_1 B - \phi_2 B^2 - \cdots - \phi_p B^p)z_t = (1 - \theta_1 B - \theta_2 B^2 - \cdots - \theta_q B^q)a_t \tag{4}$$

Applying the polynomial operators to z_t and a_t, this model may be re-expressed as

$$z_t - \phi_1 z_{t-1} - \phi_2 z_{t-2} - \cdots - \phi_p z_{t-p} = a_t - \phi_1 a_{t-1} - \phi_2 a_{t-2} - \cdots - \phi_p a_{t-p} \tag{5}$$

or

$$z_t = \phi_1 z_{t-1} + \phi_2 z_{t-2} + \cdots + \phi_p z_{t-p} + a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \cdots - \theta_p a_{t-p} \tag{6}$$

This equation defines the basic model investigated by Box and Jenkins (1970). It implies that the current observation can be represented as a linear combination of a finite number of previous observations, plus a white noise error term associated with the current time period, plus a linear combination of a finite number of white noise terms associated with previous time periods.

Let Φ (B) and Θ (B) be polynomials as defined as follows:

$$\Phi(B) = 1 - \phi_1 B - \cdots \phi_p B^p \tag{7}$$

and

$$\theta(B) = 1 - \theta_1 B - \cdots - \theta_q B^q \tag{8}$$

Then the model of equation (4) may be re-expressed as

$$\Phi(B) z_t = \Theta(B) a_t \tag{9}$$

The general model (9) is called a mixed autoregressive moving average (ARMA) process and may conveniently be used to describe processes that do not have strong cyclical trends.

Data used:

The flow data from January 1992 to December 2008 is shown in Figures 2, 3 and 4 for daily, monthly and annual scales and were studied using the techniques outlined above.

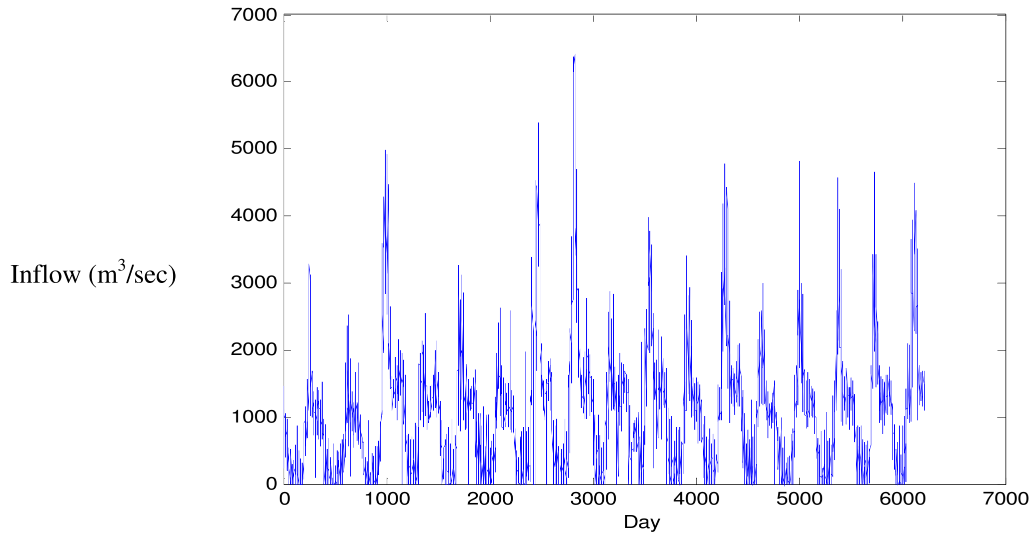

Figure 2: Plot of Daily Inflow into Kainji Dam

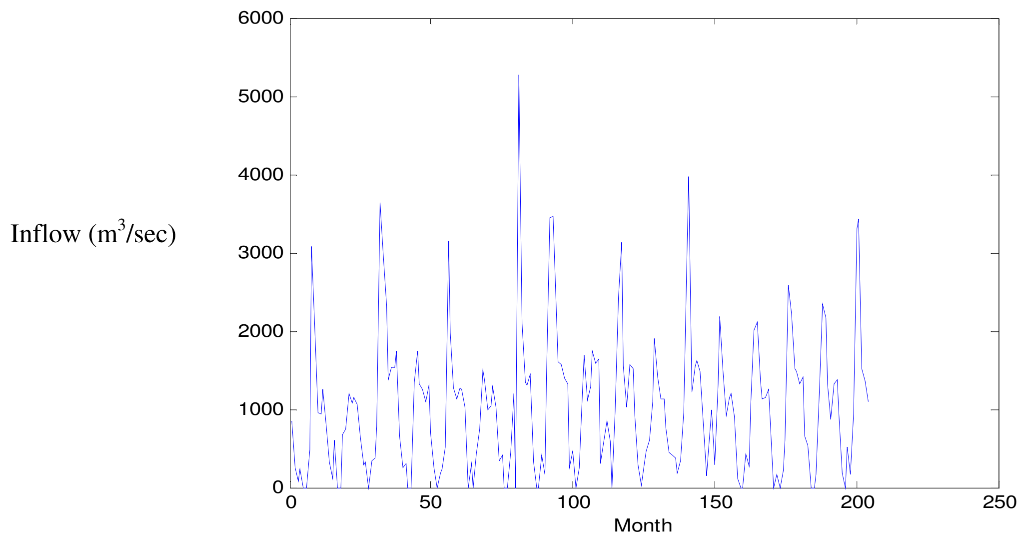

Figure 3: Plot of Monthly Inflow into Kainji Dam

The plots indicate a highly cyclical pattern in the inflow with two peaks occurring each year that correspond to the black flood and the white floods respectively. This is also indicated in the spectral plot shown in figure 5.

The annual data averages out the fast changes associated with the daily flow but reflects an overall trend which appears to be monotonically increasing. The data set from January 1991 to December 2005 is used for model development while that from January 2006 to December 2008 was used for model validation.

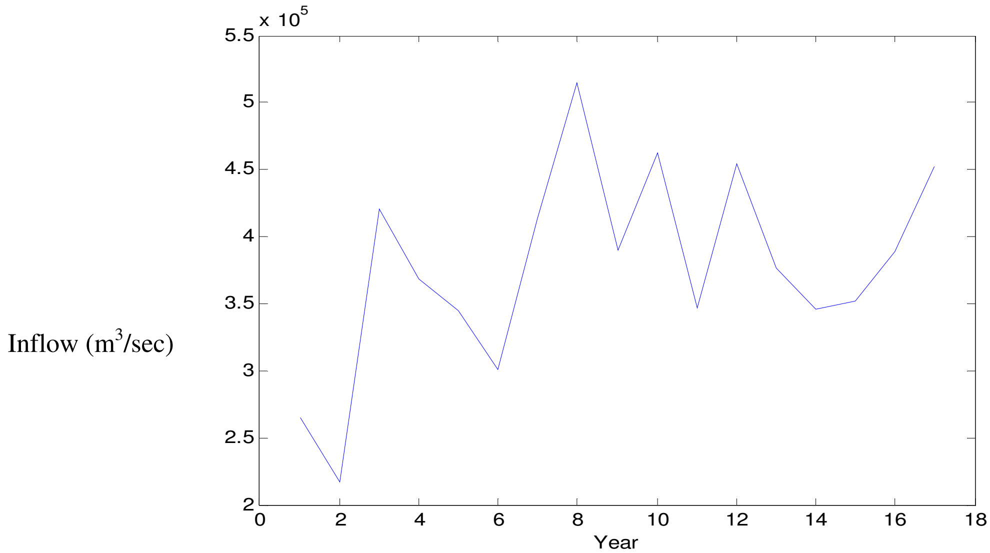

Figure 4: Plot of Yearly Inflow into Kainji Dam

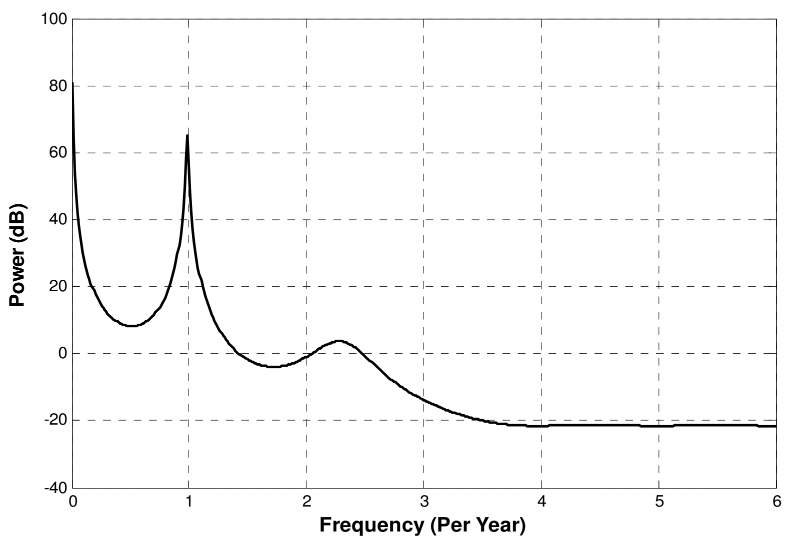

Figure 5: Power Spectrum Estimate of Inflow into Kainji Dam.

Model development and testing:

Considering the very cyclical nature of the data, it was decided that exponential smoothing technique will be employed to filter out the high frequency components of the data. In order to obtain the trend, a lowpass filter was designed to remove the higher frequency components from the series before analysis. Since the transfer function of the first order digital filter is given as

$$H(z) = \frac{z}{z-a} \tag{10}$$

$$\frac{za}{z-e^{-saT}} = \frac{y_k}{u_k} \tag{11}$$

The trend of the series can be extracted using the following equation

$$\hat{y}_{k+1} = \beta\hat{y}_k + \alpha\hat{y}_{k+1} \tag{12}$$

Where $\alpha = \text{In}\,\beta$ and $\beta = e^{-sat}$ (13)

This operation was implemented using MATLAB so that the new output or estimate is obtained as the sum of the old, new and a factor of the old output.

A second order effect was obtained by applying the filter twice with the first output fed into the second input and both outputs were summed to give an estimate of the monthly inflow. Plots of the original data and estimated trend are shown in figure 6. The residues between the two values were relatively small compared to the actual flows. This indicates that a good model for the inflow can be obtained using this relatively simple process. It however, can only provide shorter term forecasts which are very helpful for scheduling of power generation from the dam. Longer-term forecasts must include other components of the time series technique. Clearly the more complete study will require an identification of the seasonal/cyclical components of the series.

Inflow (m^3/sec)

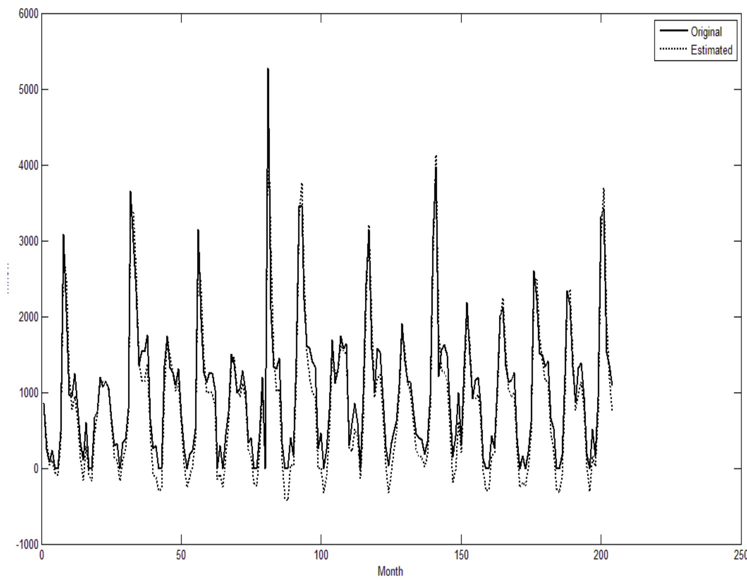

Figure 6: Plot of Original and Predicted Inflow into Kainji Dam.

The correlation of the original monthly data and the exponential trend was calculated to be 98%

CONCLUSION:

Exponential smoothing technique has been proposed for the short term forecast and synthesizing hydrological data respectively. The EST is adaptive and the feature prediction technique is novel. It provides a method by which hydrological data can be analysed satisfactorily. The technique yielded a prediction that is 98% correlated with the original data for the Kainji Dam in Nigeria, and very small dataset (at least 5 data points) is needed to estimate the parameters.

The advantage of this technique over other similar models lies in the fact that the algorithm may be implemented sequentially whereas in the erstwhile techniques, the entire data record is usually required for identification, estimation and diagnostic checking. The number of parameters to be estimated in the implemented technique is two (one of them can in fact be estimated from the other).

It is expected that the applications of this technique to the analysis and synthesis of stream/river flows would yield very useful results in the design and operation of several hydraulic structures. The EST and the feature prediction techniques may be applied to other random processes in control, communication, social and other systems.

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