

STATISTICAL ANALYSIS AND MODEL FITTINGS FOR OPERATIONAL PARAMETERS AT JEBBA HYDROPOWER DAM, NORTH CENTRAL NIGERIA

¹A.W. Salami, and ^{2*}O.A. Mokuolu

^{1,2}Department of Water Resources and Environmental Engineering, University of Ilorin, Nigeria.

*Corresponding author's email: - olubunmimokuolu@yahoo.com

Abstract

This paper focuses on statistical analysis and model fittings of operational parameters at Jebba Hydropower Dam. The operational parameters available for 31-year period (1984 – 2015) which include reservoir inflow, elevation, turbine release, generating head, energy generation and tailrace water level was obtained from Jebba Dam Station. The linear trend model was developed by adopting least square technique; the equations obtained were used to forecast the parameters with respect to time. In order to test the level of fitness of the model, statistical goodness of fit tests were carried out in accordance to standard procedure. The tests include chi-square (χ^2), correlation coefficient (r), coefficient of determination (R^2), Root mean square error (RMSE), and Mean Absolute Error (MAE). It was revealed that for the reservoir inflow, there appears to be large errors of the RMSE and MAE but with reasonable results for the chi-square, correlation coefficient and coefficient of determination. The same was identified for turbine release and energy generation. The reservoir inflow was also fitted to normal distribution; the reservoir inflow was forecasted for 75%, 90% and 95% probability of exceedance. The study inferred that the model developed adequately fit the parameters and can be used for prediction purposes.

Keyword: Jebba Hydropower Dam, Operational parameters, least square technique, normal distribution, goodness of fit test

Introduction

The operations of the Jebba hydropower schemes and runoff from catchments govern the flow regime of the Jebba dam. Releases from Kainji hydropower dam constitute the major inflow into Jebba hydropower dam since it lies directly under it. This means that the more the release from upper reservoir, the faster the downstream reservoir fills up and the excess will be discharged thereby leading to flooding. The communities in the flood plains experience annual flooding when the authorities of dam station open the gates of the dams to let off water at the peak of the

rains. The occurrence of flood has great effect on communities and farming activities downstream of Jebba dam (Salami, 2007). In the same vein, the inability of the hydropower stations to operate at installed capacity could be attributed to the following reasons:

- i. Hydrological factors such as: seasonal variation in flow to the reservoir; inter-annual variation in flow to the reservoir; conflict among competitive uses; and sediment trapped in the reservoir.
- ii. Non-hydrological factors such as: maintenance and spare parts problems; inadequate funding; human resources; and policy issues.

Most studies on hydropower systems operations primarily focus on multiple uses of water in order to satisfy human needs and demands connected to economic and social activities. Brandao (2012) expressed that water resources exploitation and control systems to satisfy human needs include power generation, urban and industrial water supply, irrigation, navigation, flood control and water pollution control.

The combined installed capacity of power stations in Nigeria is far below the country's electricity demand, resulting in epileptic supply of electricity. The situation is compounded by the failure of the existing power stations to operate at their installed capacity (Batalla, 2004). The potential for hydropower is usually assessed in terms of overall energy output, the maximum suitable installed power generation capacity and the typical variations in power production. Some factors such as fluctuations in demand, limitations in the power transfer grid, river discharge fluctuations and the feasibility of water storage and creating a head fall for energy production affect this potential (Worman, 2012).

The operations of reservoir play an important role in protecting people and their socio-economic activities in flood plains areas. In order to measure the hydrologic impacts of dams on the monthly level, Ritcher et al. (1996) accounted for two characteristics; i.e. magnitude and duration of flows, while Lajoie et al. (2007) considered the influence of watershed size and seasons. Additionally, some researchers took into account the root mean square error (Hanasaki et al., 2006), coefficient of variation or coefficients of skewness (Maheshwari et al., 1995), to evaluate the hydrological alteration by reservoirs. Climate change may affect water resources and may lead to significant variations of the potential for hydropower at a country level, these variations are expected to cancel out roughly on the global scale, leaving the overall potential virtually unaffected (Fahmy et al., 1994; Nogueira et al., 2008; Bosona and Gebresenbet, 2010).

Hydropower generations in Nigeria is estimated to be about 35.6% of the Nigeria's electricity sources with gas estimated at 39.8% and oil, 24.8% (Obadote, 2009). Because of the insufficiency of gas, hydropower has a larger advantage in that, once it is constructed, electricity can be produced at a constant rate. A range of factors limit hydropower potential which includes river discharge and its variation, landscape topography and environmental considerations, technical capacity, e.g., turbine design, limitations of the electrical transmission system, technical flaws and functionality of the energy market (Worman, 2012). It was expressed by Worman et al. (2010), that the annual discharge of rivers limits the overall energy from hydropower plants.

The determination of the size of reservoir for a specified purpose such as flood control is based on hydrologic analyses that are governed by project formulation criteria. It is recognized that maintaining (in the case of new dams) or re-establishing (in the case of existing dams) the natural river condition by managed flow may not always be possible and may require a conflict management mechanism to adopt the approach. In addition, as the available resources cannot meet the demands of all purposes in a given system, it is essential to objectively evaluate the system potential and the best form of operation. Therefore this study emanates from the need to assess Jebba Hydropower Dam operational parameter through model fitting for prediction purposes.

2.0 Methodology

2.1 Description of Study Area

Jebba Hydroelectric Power Station is along River Niger, Nigeria, located between latitudes $9^{\circ} 10' \text{ N}$ to $9^{\circ} 55' \text{ N}$ and longitudes $4^{\circ} 30' \text{ E}$ to $5^{\circ} 00' \text{ E}$ at 76 m above sea level (about 100 kilometers downstream of Kainji dam). The station is one of the most cost-effective sources of electricity in Nigeria. It has maximum length of 100 kilometers (km), maximum depth of 32.5m, maximum width of 10 km and a mean depth of 3.3 m. The surface area is 350 km^2 , maximum volume of $1000 \times 10^6 \text{ m}^3$, operating head of 27.6 m and maximum flow per unit of $380 \text{ m}^3/\text{s}$. The dam, which has a generating capacity of 540 MW from six (6) turbines of 95 MW of power each, is enough to power over 364, 000 homes at operating head of 27.6 m. Each turbine is coupled to a generator of 119 MVA maximum continuous rating and 103.50 MVA base load rating. The dam was developed and constructed in 1979 and there has been no overhaul of the dam since inception. However, the station has been able to carry out routine minor and major repair works,

and preventive maintenance which has kept the station performance well above average. Figure 2.1 show the location of Jebba Hydropower Dam on the Nigeria map and Table 2.1 presents the basic data on Jebba Hydropower System.



Figure 2.1: Location of Jebba Hydropower Dam on Nigeria map

Table 2.1 Basic Data on the Jebba Hydropower System

Description of parameters	Values
First year of operation	1984
Installed Capacity (MW)	540
Design power plant factor	0.70
No, of generators	6
Reservoir flood storage capacity (Mm ³)	4,000
Reservoir flood level (m)	103.55
Water Surface Area (Km ²) at EL 103.0 m	303.00
Maximum operating reservoir elevation (m.a.s.l)	103.00
Minimum operating reservoir elevation (m.a.s.l)	99.00
Maximum storage (Mm ³) (active storage capacity)	3,880
Minimum storage (Mm ³) (dead storage capacity)	2,880

Source: Power Holding Company of Nigeria (PHCN) 2012 cited in Adejumo (2012)

2.2 Data Collection and Analysis

The data collected are reservoir inflow (I), storage (S), elevation (H), turbine release (Q), energy generation (E), and tail race water level (T) for period of 31 years (1984 – 2015) at the Jebba Hydropower station. The mean values of the operational parameters are presented in Table 2.2.

Table 2.2 Mean values of operational parameters (1984 - 2015)

Month	Inflow, I (10 ⁶ m ³)	Reservoir Storage, S (10 ⁶ m ³)	Reservoir elevation, H (m)	Turbine release (10 ⁶ m ³)	Energy generation, E (MWH)	Tail water race, T (m)
J	2816.34	3486.86	101.81	2923.58	201149.2	73.92
F	2494.06	3537.71	101.74	2604.83	179092.5	73.77
M	2534.55	3523.36	101.77	2527.23	183426.2	73.67
A	2476.57	3482.14	101.65	2529.42	174818.9	73.58
M	2348.31	3467.43	101.54	2338.30	167722.0	73.43
J	2167.84	3463.46	101.41	2212.31	155854.9	73.33
J	2074.62	3385.64	101.11	2083.62	150044.0	73.22
A	2784.15	3437.00	101.42	2772.19	179755.6	73.63
S	4233.31	3633.43	102.13	3199.80	223874.2	74.37
O	4404.78	3689.46	102.35	3558.63	235006.1	74.58
N	2699.38	3551.11	101.82	2673.61	191259.0	73.84
D	2908.65	3521.56	101.72	2737.17	189999.9	73.79

2.3 Estimation of Reservoir Inflow of Various Probabilities of Exceedence

The reservoir inflow was fitted into normal distribution based on the monthly mean and standard deviation of the historical data. The normal models obtained for the month of January to December are presented in equations (2.1) to (2.12) respectively, the predicted reservoir inflow of 50%, 75%, 90%, and 95% probabilities of exceedence and statistical parameters are presented in Table 2.3.

$$Q_{January} = 2816.34 + 999.71K \quad (2.1)$$

$$Q_{February} = 2494.06 + 819.14K \quad (2.2)$$

$$Q_{March} = 2534.55 + 857.25K \quad (2.3)$$

$$Q_{April} = 2476.57 + 752.28K \quad (2.4)$$

$$Q_{May} = 2348.31 + 748.76K \quad (2.5)$$

$$Q_{June} = 2167.84 + 615.30K \quad (2.6)$$

$$Q_{July} = 2074.62 + 787.14K \quad (2.7)$$

$$Q_{August} = 2784.15 + 1223.48K \quad (2.8)$$

$$Q_{September} = 4233.31 + 1950.59K \quad (2.9)$$

$$Q_{October} = 4404.78 + 2548.70K \quad (2.10)$$

$$Q_{November} = 2699.38 + 877.80K \quad (2.11)$$

$$Q_{December} = 2908.65 + 693.42K \quad (2.12)$$

Where k is parameter depending on the probability of exceedance or return period and can be obtained from standard hydrological books.

Table 2.3 Reservoir Inflow of Different Reliabilities

Month	Probability of exceedance			Mean flow (Mm ³)	Standard Deviation (Mm ³)
	75%	90%	95%		
Jan	2136.54	1526.71	1171.82	2816.34	999.71
Feb	1937.04	1437.37	1146.57	2494.06	819.14
Mar	1951.62	1428.70	1124.38	2534.55	857.25
Apr	1965.02	1506.13	1239.07	2476.57	752.28
May	1839.15	1382.41	1116.60	2348.31	748.76
Jun	1749.44	1374.10	1155.67	2167.84	615.30
Jul	1539.36	1059.21	779.77	2074.62	787.14
Aug	1952.18	1205.86	771.52	2784.15	1223.48
Sept	2906.90	1717.04	1024.58	4233.31	1950.59
Oct	2671.67	1116.96	212.17	4404.78	2548.70
Nov	2102.48	1567.02	1255.41	2699.38	877.80
Dec	2437.13	2014.14	1767.98	2908.65	693.42

2.4 Model Fitting for Hydropower Variables

The model identification method used to fit the model is the least square technique. In this case, the monthly average inflow, storage, elevation, turbine release, energy production and tailrace water level of Jebba Hydropower station for 31 years were used. The model fitting process was

done by computing the trend components of the respective data with parameters α and β using the equation (Zara and Karamouz, 2004).

$$\text{Linear Trend} \quad T = \alpha t + \beta \quad (2.13)$$

The linear trend model was obtained by fitting the parameters with the corresponding time, the components α (slope) and β (intercept) were obtained and the linear trend models were established for each parameter. In order to determine the level of fitness, statistical tools such as chi-square, (χ^2), correlation coefficient, (r), coefficient of determination, (R^2), Root mean square error, (RMSE), and Mean Absolute Error, (MAE) were adopted. The details about the statistical goodness of fit tests are presented as follows.

2.5 Statistical Goodness of Fit Tests

The acceptability and reliability of the probability distribution was tested by using statistical goodness of fit tests. The statistical tests include chi-square (χ^2), the probability plot coefficient of correlation (r), and the coefficient of determination (R^2). The statistical tests were carried out in accordance with standard procedure (Chowdhury and Stedinger, 1991; Adegboye and Ipinoyomi, 1995; Murray, 1974; and Murray and Larry, 2000).

2.5.1 Chi-square (χ^2) test

The predicted values of the parameters with established model was compared with the observed values and the chi-square was used to determine how well the theoretical distribution fits the empirical distribution. This test was based on the sum of the squares of difference between the frequencies. The expression for the analysis of chi-square is

$$\chi^2 = \sum_{j=1}^N \frac{(o_j - e_j)^2}{e_j} \quad (2.14)$$

where: o = observed flow; e = predicted flow and N = total frequency

Murray and Larry, (2000) stated that if the computed value of chi-square is greater than some critical value (such as $\chi^2_{0.95}$ or $\chi^2_{0.99}$ which is the critical values at the 0.05 and 0.01 significance level respectively), it could be concluded that the observed frequencies differ significantly from the expected frequencies and it would be rejected, otherwise it would be accepted. Hence, if the χ^2 value calculated from equation (2.14) is less than critical value from statistical table, the

model can be concluded to be strong or the fit of the data is good. Another way by which the conclusion can be made is that if the value of the ratio of calculated chi-square to the tabulated chi-square ($\chi^2_{\text{cal}} / \chi^2_{\text{tab}}$) is less than one, the probability distribution is strong. The distribution function that gives value very close to 1 is the best for the data (Murray and Larry, 2000).

2.5.2 Probability Plot Correlation Coefficient (PPCC)

This is used to evaluate the linearity of the probability plot, so that if the sample is actively drawn from the hypothesized distribution the PPCC (r) is expected to be close to one. The quantity (r) called coefficient of correlation is given as:

$$r = \pm \sqrt{\frac{\sum (Q_{\text{est}} - Q_{\text{mean}})^2}{\sum (Q_{\text{obs}} - Q_{\text{mean}})^2}} \quad (2.15)$$

Where:

Q_{est} = the value of inflow estimated with the probability function

Q_{mean} = the mean value of the observed inflow and Q_{obs} = the value of the observed Inflow

2.5.3 Coefficient of Determination (R^2)

This is a measure of the strength of relationship between the predictor and response variables. According to Dibike and Solomatine (1999), the coefficient of determination in the regression theory is defined as:

$$R^2 = \frac{E_o - E}{E_o} \quad (2.16)$$

Where:

$$E_o = \sum_{i=1}^N (Q_{i(\text{obs})} - Q_{i(\text{mean})})^2 \quad (2.17)$$

$$E = \sum_i^N (Q_{i(\text{obs})} - Q_{i(\text{est})})^2 \quad (2.18)$$

$Q_{i(\text{est})}$ is the model output in the i^{th} time period, $Q_{i(\text{obs})}$ is the observed data in the same period and $Q_{i(\text{mean})}$ is the mean over the observed periods. The model is strong, if R^2 is very close to one.

2.5.4 Error of estimate

Two errors of estimate were taken into consideration for comparison of results in accordance to Antonopoulos et al. (2001). The first of them is the Root Mean Square Error (RMSE), which is given as:

$$RMSE = \sqrt{n^{-1} \sum_{i=1}^n \{Q_{obs}(i) - Q_{pred}(i)\}^2} \quad (2.19)$$

The second is the Mean Absolute Error (MAE), which is defined as

$$MAE = n^{-1} \sum_{i=1}^n |Q_{obs}(i) - Q_{pred}(i)| \quad (2.20)$$

The linear trend models developed for each parameter along with the statistical tool are presented in Table 2.4.

Table 2.4 The linear trend models developed for each parameter along with the statistical goodness of fit

S/N	Parameters	Linear trend Model $T = \alpha t + \beta$	Performance level based on statistical tools				
			χ^2	r	R ²	RMSE	MAE
1	Reservoir inflow	$T = 90.74t + 2238.71$	0.80	0.98	0.95	636.61	503.48
2	Reservoir storage	$T = 7.88t + 3463.74$	0.01	0.99	0.97	74.80	59.33
3	Reservoir elevation	$T = 0.02t + 101.58$	0.00	0.99	0.99	0.31	0.24
4	Turbine releases	$T = 36.06t + 2445.67$	0.33	0.99	0.98	373.07	291.48
5	Energy generation	$T = 2180.01t + 171830.16$	0.23	0.99	0.98	22700.22	18149.54
6	Tail race water level	$T = 0.03t + 73.54$	0.00	0.99	0.98	0.36	0.29

R² = Coefficient of determination, χ^2 = Chi-square, r = Correlation coefficient, RMSE = Mean Square Error, MAE = Mean Absolute Error

The monthly trends of the observed and measured reservoir inflows, storage, elevation, turbine release, energy generation and tailrace water level were determined and presented in Figures 2.2 to 2.7, respectively.

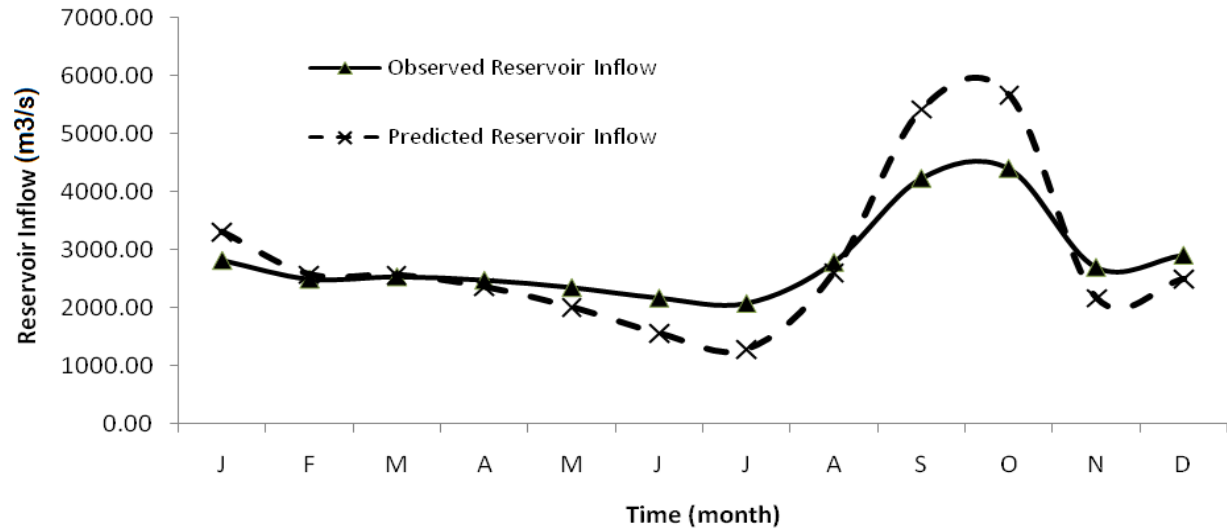


Fig. 2.2. Model Fitting for Reservoir Inflow of Jebba Hydropower Dam

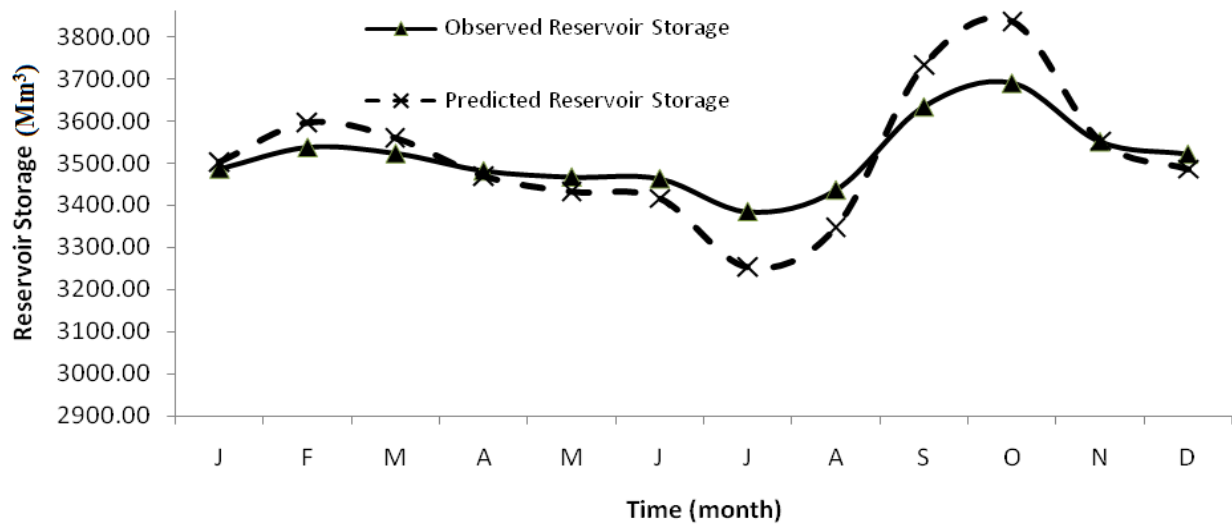


Fig. 2.3. Model Fitting for Reservoir Storage of Jebba Hydropower Dam

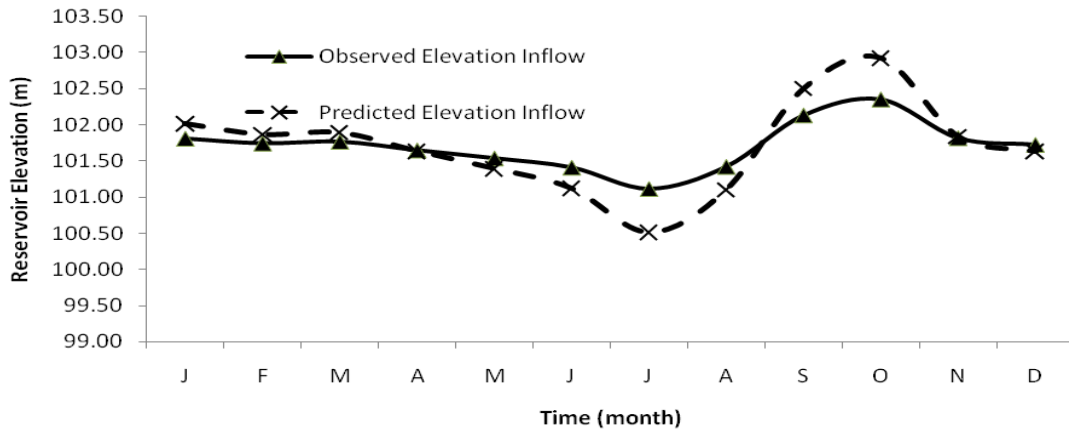


Fig. 2.4. Model Fitting for Reservoir Elevation of Jebba Hydropower Dam

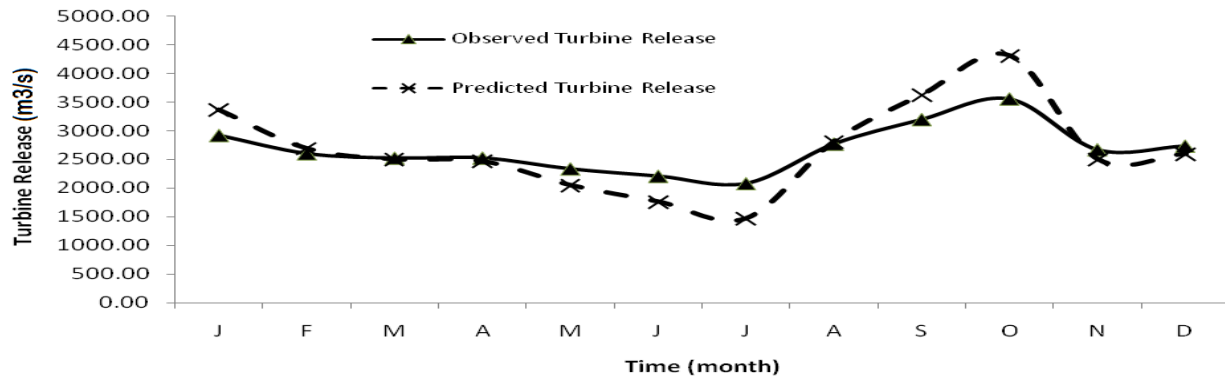


Fig. 2.5. Model Fitting for Turbine Release of Jebba Hydropower Dam

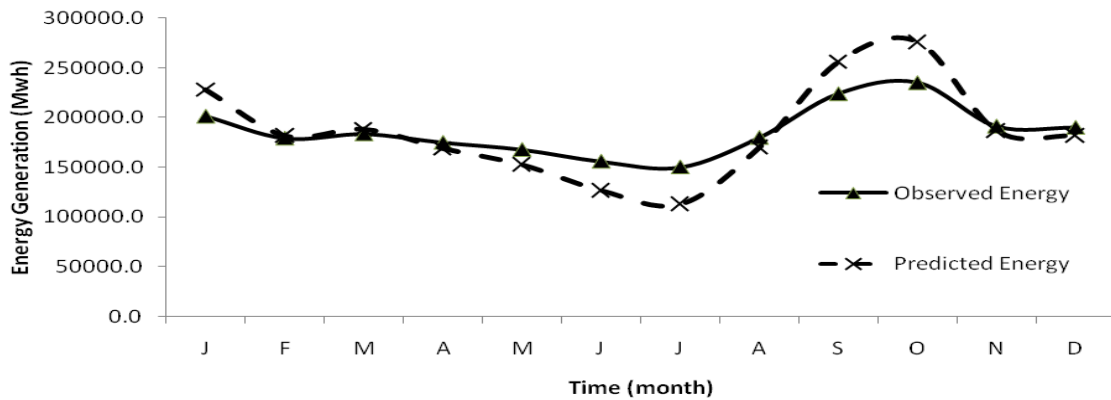


Fig. 2.6. Model Fitting for Energy Generation of Jebba Hydropower Dam

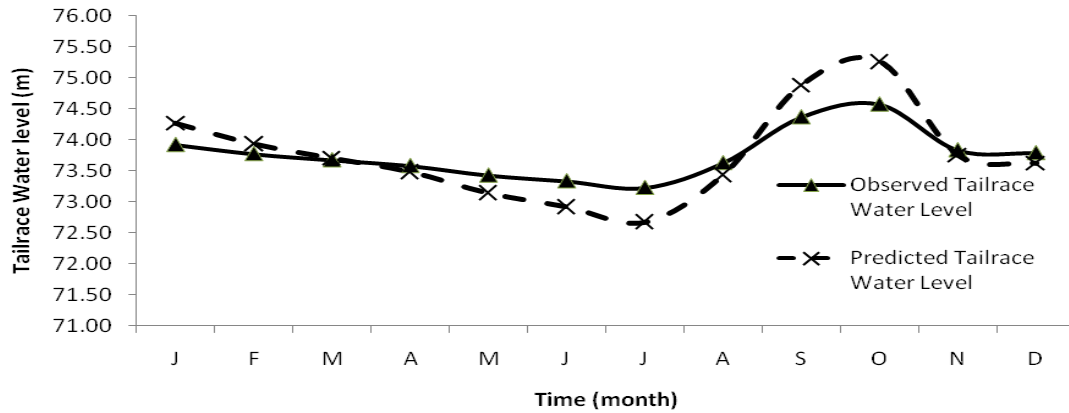


Fig. 2.7. Model Fitting for Tailrace Water Level of Jebba Hydropower Dam

Results and Discussion

Table 2.2 showed the average monthly statistical summaries for reservoir inflow, storage, elevation, turbine release, energy generated and tailrace water level, respectively, for periods of 1984 - 2015. As indicated in Table 2.2, the peak value of the reservoir inflow occurs during the month of October ($4404.78 \text{ m}^3/\text{s}$), while the low flow occurred during the month of June. This consequently influences the storage of the reservoir as shown in Table 2.2 with a storage value of (3689.46 m^3). During the 31 years of operation (1984 – 2015), the peak average reservoir elevation was 102.35 m, while the lowest average reservoir elevation was 101.11 m.

The least square technique was adopted to fit the model i.e equation (2.13). The fitted models and the statistical goodness of fit tests (such as the chi-square, correlation coefficient, root mean square error, coefficient of determination and the mean square error), are presented in Table 2.4. The monthly trends of the observed and measured reservoir inflows, storage, reservoir elevation, turbine release, energy generation and tailrace water level were determined and presented in Figures 2.2 to 2.7, respectively. The high spread of inflow, storage, energy generation and turbine release is a significant pointer that the hydrological process is not being uniform throughout the years (stochastic). It is also clear that the four parameters (inflow, storage, energy generation and turbine release) are closely related. The pattern is similar with higher values in September-October and lower values in June-July. This seasonal routine is identified as an important factor influencing the functioning of the reservoir servicing the Hydropower dam. It

was observed that the mean expectations on both the observed and estimated parameter values are the same for all parameters of inflow, storage, elevation, turbine release, energy generation and the tailrace water level. For the reservoir inflow, there appears to be large errors of the RMSE and MAE but with reasonable results for the chi-square, correlation coefficient and coefficient of determination. The same was identified for reservoir storage, turbine release and energy generation. The other three parameters have all the values of the fitness test within the limit of good fit. The model fitting charts for all the parameters (Figures 2.2- 2.7) show that, the predicted values begun slightly above the observed values and ends slightly below the observed values. In the probability of exceedence (reliability of flow) computed using normal distribution (Table 2.3), the values are in descending orders in the order of 75%, 90% and 95% respectively.

Conclusion

Modeling the operational parameters at Jebba hydropower dam was carried out. It involved the development of the linear trend model based on least square method. The model developed was used to predict and the level of fitness was ascertained by adopting statistical goodness of fit tests. The outcome of the fitness tests revealed the adequacy of the model. The normal distribution was also fitted to reservoir inflow in order to forecast for various probability of exceedence, (reliability) the outcome revealed that reservoir inflow decreases as the probability of exceedence, (reliability) increases.

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