Optimization of Energy Generation at the Kainji Hydropower Reservoir

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Abstract

Operation and management of water resources for various uses like: domestic water supply, irrigation and hydroelectricity generation requires optimization techniques for efficient reservoir operation. This study was carried out to optimize energy generation at Kainji hydropower dam in Nigeria using operations and ecological requirement constraints. Optimization approach was used to optimize mean total annual energy generation subject to operation and ecological constraints. The model was solved using Language INterative General Optimization (LINGO) version 17.0 software. Results showed that the optimization approach will increase the total annual energy generation at the station by over 1%. This result can be adopted by the management of the hydropower station and other decision makers in Nigeria to improve the hydropower generation to be made to the Nigeria National grid without negative impact on the ecological integrity of the reservoir.

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1.1 Introduction

Optimization of reservoir operation is very vital in improving reservoir outputs and has been widely investigated in the past (Homa *et al.*, 2005; Chang *et al.*, 2005; Adeyemo, 2011; Usman and Ifabiyi, 2012; Chen *et al.*, 2013). A conventional hydropower reservoir operation practice is mostly guided by maximizing energy generation without taking into consideration the ecological requirements of the reservoir. This practice may greatly affect natural phenomena, especially water and sediment qualities with fish availability in a reservoir (Mohammed, 2018). Belayneh and Bhallamudi (2012) used optimization model for management of water quality in a tidal river, Chennai, India using upstream releases. It was demonstrated that the total upstream release volume can be minimized, while maintaining desired water quality. Shaw *et al.* (2017) optimized a multipurpose hydropower reservoir near Nashville, Tennessee in USA using a predictive power CE-QUAL-W2 model integrated into a genetic algorithm optimization approach subject to operation and water quality constraints. The optimization will increase hydropower production by 6.8 and 6.6% for dissolved oxygen (DO) limits of 5 and 6 mg/l respectively.

Sule *et al.* (2018) evaluated the reservoir yield and hydropower potential of Doma Dam, Nasarawa State, Nigeria using ANN model in ALYUDA Forecaster XL to extend the available streamflow record at the location. It was observed that at 50, 75 and 100% usage of the excess stored water with a head of 20 m, the power potentials increases. Huang *et al.* (2013) used chaotic genetic algorithm to optimize hydropower generation with ecological consideration. Results indicated that the proposed model and algorithm were scientific and feasible to deal with the optimal operation of hydropower generation with ecological consideration.

Niu and Zhang (2002) applied LINGO to optimize water supply system in a city in China. Results showed that the LINGO was so precise that the differences between the estimated and actual service flow rate were very small. Dutta (2015) determined the reservoir capacity of Gadana dam in India using linear programming. The model was analyzed using LINGO software in which values of the reservoir were provided and the reservoir capacity was determined. Ahmed *et al.* (2013) optimized yield of Dokan reservoir system in Iraq using LINGO. Two linear programming (LP) models were developed for estimating the maximum safe yield with allowable deficit. The annual reservoir yield was estimated as 5653.8 Mm^3/year.

Salami *et al.* (2017) evaluated hydropower potential at Doma dam in Nassarawa State, Nigeria using optimization techniques. The model was solved with LINGO 10.0 software for various mean annual inflow exceedence probabilities. Results revealed that the dam is suitable for hydropower generation between 0.61 and 0.70 MW. Parsa (2017) optimized Karun reservoir in Iran using linear programming. Results showed good compliance between the linear programming model with optimal values and historical observations. Mohammed *et al.* (2018) optimized reservoir yield in the Kainji lake basin based on operations and ecological integrity requirements using LINGO software. It was discovered that the optimum yields of 1761.19 and 1590.49 Mm^3 can be withdrawn from the lake with and without considering the effect of ecological integrity constraints respectively.

Management of reservoir system is complex due to dimensionalities, nonlinearities and conflicts between different objectives. Optimal operation of reservoir system typically involves optimization and simulation models (Lin and Rutten, 2016). Optimization model is used to minimize or maximize an objective function under given constraints and the simulation model is used to examine how water system behaves under a set of conditions. In the past, optimization problems have been solved by LP, dynamic programming (DP), quadratic programming (QP) and non-linear programming (NLP) (Lin and Rutten, 2016). Symum and Ahmed (2015) used LP to optimize water supply and cropping area for irrigation in Bangladesh. An optimization model was formulated to maximize profit from cultivation while satisfying constraints like cropping area, irrigation water supply, cropping cycle and market demand. The results provided optimum value for cropping area and irrigation water depth that maximize the objective function.

Mahsafar *et al.* (2017) optimized allocation of agriculture water for irrigation of multiple crops using nonlinear programming in Iran. The model was solved using LINGO solver package. The results showed that optimizing the cropping patterns along with proper allocation of irrigation water had substantial potential to increase the net return of agricultural water. Deeprasertkul (2015) used LP for optimal reservoir operation of Chao Phraya river basin in Thailand. The results revealed that the optimal solutions were comparable to the actual volume of water stored and released from the reservoir. Several optimization methods have been used in reservoir operations, depending on characteristics of reservoir system, specific objectives, system constraints and data availability (Khare and Gajbhiye, 2013).

The existing reservoir operation at Kainji dam has been characterized by variants of problem such as annual flooding and ecological modification around the dam area. This has impacted negatively on the generation capacity of the dam. In this study LINGO optimization software was used due its availability, effectiveness and accuracy in handling this problem. LINGO is a comprehensive tool designed to make, build and solve various optimization problems. It provides a complete integrated package that includes a powerful language for expressing optimization models (Dutta, 2015). Most water resources allocation problems are addressed using LP (Simonovic, 2009). Optimization model for reservoir operations generally consists of objective function and constraints (Chen *et al.*, 2013).

1.2 Description of study area

The Kainji dam is located in New Bussa, Borgu Local Government Area of Niger State, Nigeria. Kainji hydropower reservoir is fed by many tributaries. It lies at an altitude of 108 m above sea level, between Yelwa (latitude 10° 53'N: longitude 4°45'E) and Kainji (latitude 9° 50'N: longitude 4°35'E). Figure 1 is the Map of Nigeria showing location of Kainji lake. It is underlained by basement complex rocks such as porphyritic granite, mica and quartzite (Ifabiyi, 2011).

The reservoir that resulted from Kainji dam was built between 1964 and 1968 and commenced operation in 1968 for the purpose of generating electricity (Ifabiyi, 2011). The maximum water surface elevation is 141.9 mean above sea level (masl). Kainji Lake is the largest man-made lake in Nigeria with a surface area of 1270 km^2. The storage capacity is 15 x 10^9 m^3 with a total live storage of 12 x10^9 m^3. Kainji hydropower reservoir has an installed capacity of 760 MW. The maximum length, maximum width, maximum and mean depths are 136.8 km, 24.1 km, 60 m and 11 m respectively. Kainji reservoir is characterized by prolonged high temperature, low rainfall and low relative humidity; it exhibits evaporation values that are in excess of rainfall (Abam, 2001). The dam has eight plants with total installed capacity of 760 MW (four-80 MW, two-100 MW and two-120 MW). The spillway is equipped with radial gates having a total spilling capacity of 7,900 m^3/s (Jimoh, 2008). Figure 2 is the Google imagery of Kainji reservoir indicating sampling locations. The sampling locations and their corresponding coordinates are presented in Table 1. Four ecological indicators approved by Tennessee Valley Association (TVA), USA to monitor and rate overall ecological health of a reservoir as presented in Table 2 was adopted in this study in formulating ecological integrity constraint (Sharma and Sharma, 2003).

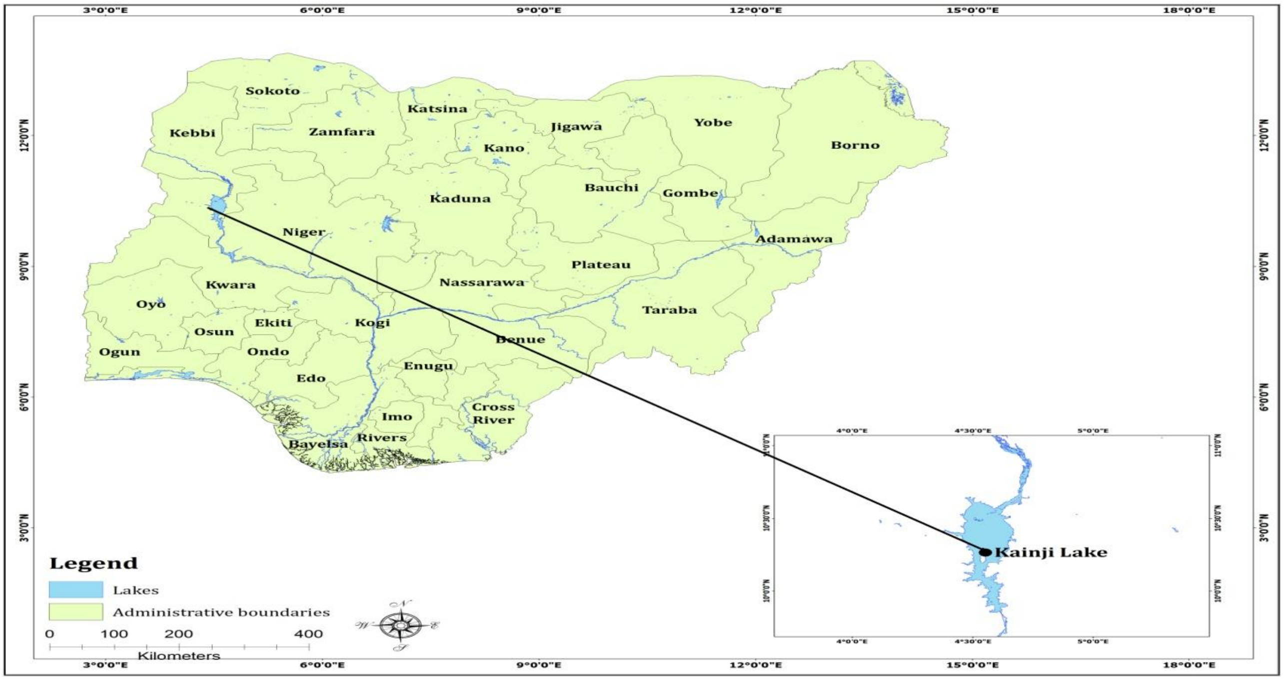

Figure 1: Map of Nigeria showing location of Kainji lake

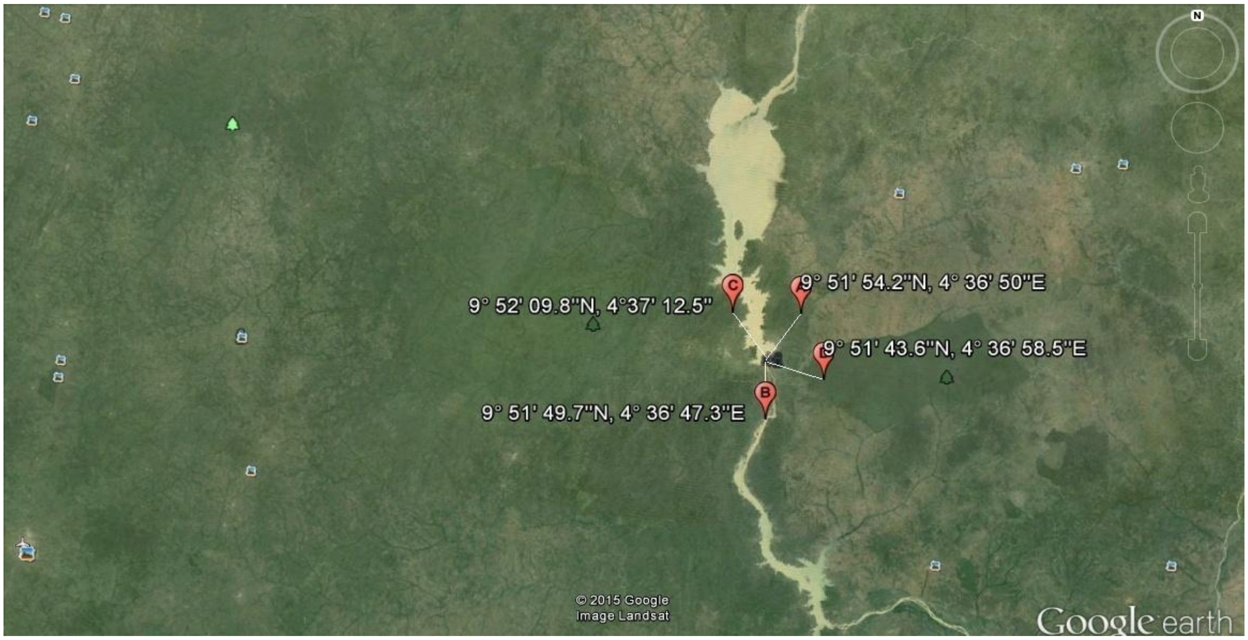

Figure 2: Google imagery of Kainji Reservoir Showing Sampling Locations

Table 1: Sampling locations and coordinates

Sampling Location	Description	Latitude	Longitude
A	Power Intake	4° 36' 50.0"	9° 51' 54.2"
B	Tailrace	4° 36' 47.3"	9° 51' 49.7"
C	Boatyard	4°37' 12.5"	9° 52' 09.8"
D	Downstream Tailrace	4° 36' 58.5"	9° 51' 43.6"

Table 2: Key indicators to monitor ecological health of a reservoir

S/No	Key indicator	Good rating means
1	Dissolved oxygen	Enough oxygen throughout the water column
2	Algae	Enough nitrogen and phosphorus to simulate the growth of algae.
3	Sediment quality	Reservoir is not polluted by chemicals.
4	Fish	There are a much population and variety of fish.

Source: Adapted from Sharma and Sharma (2003)

1.3 Aim and Objectives

The aim of this study is to optimize energy generation at Kainji hydropower station in Nigeria based on operations and ecological integrity constraints.

The objectives were to:

1. collect and analyse operation and ecological data of the reservoir.
2. formulate linear optimization problem using operation and ecological integrity data.
3. solve the formulated problem with LINGO 17.0.

2.0 Methodology

Hydropower operation data between 1970 to 2016, water and sediment quality data between 2010 to 2015 were collected from hydrological and environmental departments of Kainji hydropower station respectively. Data on fish yield between 1995 to 1998 was also collected from National Institute for Freshwater Fishery Research (NIFFR), New Bussa, Nigeria. The data collected was subjected to monthly variation and statistical analysis using Statistical Package for Social Sciences (SPSS) version 16.0. Average mean monthly data were used in the formulation of objective function and constraints. The study was carried out at four sampling locations selected on the upstream and downstream sides of the Kainji hydropower station.

2.1 Development of reservoir optimization model

Reservoir operation optimization model commonly consists of an objective function and constraints (Chen *et al.*, 2013).

2.1.1 Objective function

According to the core function of the Kainji reservoir, the annual hydropower energy generation E (MWh) is used as objective function in the model (Salami, 2007). This is presented in Equation 1.

$$Z = \max \sum_{t=1}^{12} E_t \qquad (1)$$

where:

Z = total annual energy generation (MWh)
E_t = monthly energy generation (MWh)
i = time step (month)

Energy can be estimated using Equation 2

$$E = 2.73 RH\varepsilon \qquad (2)$$

Substituting equation 2 in 1, gives Equation 3

$$Z = Max\ 2.73 \sum_{t=1}^{12} R_t H_t \varepsilon \tag{3}$$

where:

R_t = turbine release for period, t (Mm^3)

ε = hydropower plant efficiency (%)

H_t = net head on the turbine (m) = reservoir water level - tail race water level

The product of R_t and H_t in Equation 3 gives non-linear function. This is linearized by adopting Taylor's series expansion (Salami, 2007). If the average release, R_t° and average head H_t° are available for period (t) then one can write (Loucks *et al.*, 1981) the linear form as presented in Equation 4.

$$R_t H_t \approx R_t^{\circ} H_t + H_t^{\circ} R_t - R_t^{\circ} H_t^{\circ} \tag{4}$$

On substituting Equation 4 into 3, this results in Equation 5.

$$Z = \text{Max } 2.73\varepsilon \sum_{t=1}^{12} (R_t^{\circ} H_t + H_t^{\circ} R_t - R_t^{\circ} H_t^{\circ}) \tag{5}$$

To complete the objective function, the estimated mean monthly values of releases, R and net head, H are taken as R_t° and H_t°. If the product of 2.73 and the system efficiency is defined as λ therefore, the objective function becomes Equation 6. The constants associated with the objective function presented in equation 6 were estimated using the Equations 7 to 10. The mean values R_t° and H_t° are presented in Table 3.

$$Z = Max\left[\sum_{t=1}^{12} \left(a_t H_t + b_t R_t\right) - C\right] \qquad t = 1 \text{ to } 12 \tag{6}$$

$$a_t = \lambda R_t^{\circ} \qquad t = 1 \text{ to } 12 \tag{7}$$

$$b_t = \lambda H_t^{\circ} \qquad t = 1 \text{ to } 12 \tag{8}$$

$$C = \sum_{t=1}^{12} c_t = \sum_{t=1}^{12} \lambda R_t^{\circ} H_t^{\circ} \qquad t = 1 \text{ to } 12 \qquad (9)$$

$$\lambda = 2.73\varepsilon \qquad t = 1 \text{ to } 12 \qquad (10)$$

where:

R_t° = mean monthly releases (Mm^3)

H_t° = mean monthly net head (m)

a_t = coefficients for net head in the linearized objective function

b_t = coefficients for turbine releases in the linearized objective function

c_t = constants

C = summation of the constants

Table 3: Monthly mean values of turbine release (R_t°) and net head (H_t°) for Kainji dam (1970-2016)

Time, t (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
R_t^o (Mm^3)	1687.31	1710.38	1889.17	1900.44	1904.71	1911.71	1943.41	1946.59	1954.17	2022.74	2024.81	2086.46
H_t^o (m)	33.88	34.49	34.79	36.34	37.71	38.22	39.18	39.82	40.06	40.47	40.72	40.78

2.1.2 Model constraints

The objective function is to be maximized subject to operation and ecological integrity constraints.

2.1.2.1 Reservoir mass balance equation

The mass balance between inflow and outflow is given in Equation 11.

$$S_{t+1} = S_t + Q_t - R_t - L_t - G_t \qquad t = 1 \text{ to } 12 \qquad (11)$$

where:

S_{t+1} = final storage for period t + 1 (Mm^3)

S_t = initial storage for period t (Mm^3)

Q_t = reservoir inflow for period t (Mm^3)

R_t = turbine release for period t (Mm^3)

L_t = evaporation from the reservoir for period t (Mm^3)

G_t = release over spillway for period t (Mm^3)

t = time (month)

2.1.2.2 Reservoir storage constraints

The water stored in the reservoir S_t (Mm^3) should always be above the dead storage, $S_{t\ \min}$ (Mm^3) and within reservoir storage capacity $S_{t\ \max}$ (Mm^3) as presented in Equation 12.

$$S_{t\ mim} \leq S_t \leq S_{t\ \max} \qquad t = 1 \text{ to } 12 \qquad (12)$$

The reservoir capacity limit is given as

$$3000.00 \leq S_t \leq 12000.00$$

where:

$S_{t\ \min}$ = minimum reservoir capacity at time t, (Mm^3)

$S_{t\ \max}$ = maximum reservoir capacity at time t, (Mm^3)

S_t = reservoir storage at time t, (Mm^3)

2.1.2.3 Net head constraints

The available net head on the turbine, H_t (m) is restrained by the minimum and maximum net head, $H_{t\ \min}$ (m) and $H_{t\ \max}$ (m) respectively as presented in Equation 13.

$$H_{t\ \min} \leq H_t \leq H_{t\ \max} \qquad t = 1 \text{ to } 12 \qquad (13)$$

The limit on the available net is given as

$$33 \leq H_t \leq 42 \qquad t = 1 \text{ to } 12$$

where:

$H_{t\ \min}$ = minimum net head at time t, (m)

$H_{t\ \max}$ = maximum net head level at time t, (m)

H_t = available net head at time t, (m)

2.1.2.4 Turbine release (R) constraints

The available turbine release (R_t) is restrained by the minimum and maximum releases, $R_{t\,\min}$ (Mm^3) and $R_{t\,\max}$ (Mm^3) respectively as shown in Equation 14.

$$R_{t\ \min} \le R_t \le R_{t\ \max} \qquad t = 1 \text{ to } 12 \qquad (14)$$

The limit on the turbine release is given as

$$500 \le R_t \le 3900 \qquad t = 1 \text{ to } 12$$

where:

$R_{t\ \min}$ = minimum net head at time t, (Mm^3)

$R_{t\ \max}$ = maximum net head level at time t, (Mm^3)

R_t = available net head at time t, (Mm^3)

3.1.2.5 Ecological integrity constraints

In order to protect the reservoir ecological integrity; dissolved oxygen (DO), sediment quality (as a function of heavy metals like: Copper (CU), lead (PB) and chromium (CR) concentrations), algae (as a function of nitrate (NO) and phosphate (PO)) and fish population must be adequately preserved as stated by Tennessee Valley Authority (TVA) in USA (Sharma and Sharma, 2003). The DO, NO and PO data in water and the CU, PB and CR in sediment at the selected locations are available for a period of six years (2008 to 2013). The data were used in formulating the ecological integrity constraints.

3.1.2.5.1 DO indicator constraint

The concentration of DO at any location i and time t in the reservoir is more than the minimum required as per WHO and NESREA DO standards (DO_{std}) for freshwater. It is mathematically presented in Equation 15. Relationship between the mean monthly DO and reservoir storage was established using linear regression on the available data at the power intake and boatyard locations as presented in Equations 16 and 17. The relationships between the mean monthly DO and release for the turbine operations which is also the same as release at the tailrace location were also established using linear regression and are presented in Equations 18 and 19 respectively.

$$DO_{i,t} \geq DO_{std} \qquad t = 1 \text{ to } 12 \tag{15}$$

$$DO_{pi,,t} = 0.0002\mathrm{S}_{\mathrm{t}} + 4.2293 \qquad t = 1 \text{ to } 12 \tag{16}$$

$$DO_{by,t} = 0.0002\mathrm{S}_{\mathrm{t}} + 4.6768 \qquad t = 1 \text{ to } 12 \tag{17}$$

$$DO_{td,t} = 0.0038\mathrm{R}_{\mathrm{t}} - 1.5186 \qquad t = 1 \text{ to } 12 \tag{18}$$

$$DO_{tr,t} = 0.0044\mathrm{R}_{\mathrm{t}} - 2.5139 \qquad t = 1 \text{ to } 12 \tag{19}$$

where:

$DO_{i,t}$ = concentration of DO at location i and time t (mg/l)

DO_{std} = DO standard = 5.0 mg/l (Mohan *et al.*, 2013; FRN, 2011)

$DO_{pi,,t}$ = concentration of DO at power intake at time t (mg/l)

$DO_{by,t}$ = concentration of DO at boatyard at time t (mg/l)

$DO_{td,t}$ = concentration of DO at turbine discharge at time t (mg/l)

$DO_{tr,t}$ = concentration of DO at tailrace at time t (mg/l)

3.1.2.5.2 Sediment quality constraint

The concentration of heavy metals (HM) in sediment at any location i in the reservoir at time t is less than the SQGs proposed by WDOE for freshwater. It is mathematically written as in Equation 20. The heavy metals considered in this study are: CU, PB and CR. The metals were selected since their availability indicates the presence of other heavy metals in sediments (El Badaoui *et al.*, 2013). The WDOE SQG for CU, PB and CR are 80, 35 and 95 mg/kg respectively (Easthouse, 2009). The constraints for the three heavy metals are shown in Equations 21 to 23. Relationship between mean monthly CU, PB and CR with reservoir storage and release were established using the linear regression as presented in Equations 24 to 35.

$$HM_{i,t} \leq HM_{std} \tag{20}$$

$$CU_{i,t} \leq CU_{std} \tag{21}$$

$$PB_{i,t} \leq PB_{std} \tag{22}$$

$$CR_{i,t} \leq CR_{std} \tag{23}$$

$$CU_{pi,t} = 0.0034\,\mathrm{S_t} + 2.7357 \tag{24}$$

$$CU_{by,t} = 0.0031\mathrm{S_t} + 7.7667 \tag{25}$$

$$CU_{td,t} = 0.0812\,\mathrm{R_t} - 117.57 \tag{26}$$

$$CU_{tr,t} = 0.1074\,\mathrm{R_t} - 169.6 \tag{27}$$

$$PB_{pi,t} = 0.0024\,\mathrm{S_t} + 4.1885 \tag{28}$$

$$PB_{by,t} = 0.0027\,\mathrm{S_t} + 6.0905 \tag{29}$$

$$PB_{td,t} = 0.0313\,\mathrm{R_t} - 36.034 \tag{30}$$

$$PB_{tr,t} = 0.0284\,\mathrm{R_t} - 33.79 \tag{31}$$

$$CR_{pi,t} = 0.0033\,\mathrm{S_t} + 15.312 \tag{32}$$

$$CR_{by,t} = 0.005\,\mathrm{S_t} + 3.1802 \tag{33}$$

$$CR_{td,t} = 0.1393\,\mathrm{R_t} - 213.95 \tag{34}$$

$$CR_{tr,t} = 0.1211\,\mathrm{R_t} - 187.59 \tag{35}$$

where:

$HM_{i,t}$ = concentration of HM at location i at time t (mg/kg)

HM_{std} = HM standards

$CU_{i,t}$ = concentration of copper in sediment at location i at time t (mg/kg)

CU_{std} = CU standard = 80 mg/kg (Easthouse, 2009)

$PB_{i,t}$ = concentration of lead in sediment at location i at time t (mg/kg)

PB_{std} = PB standard = 35 mg/kg (Easthouse, 2009)

$CR_{i,t}$ = concentration of chromium in sediment at location i at time t (mg/kg)

CR_{std} = CR standard = 95 mg/kg (Easthouse, 2009)

$CU_{pi,t}$ = concentration of copper in sediment at power intake at time t (mg/kg)

$CU_{by,t}$ = concentration of copper in sediment at boatyard at time t (mg/kg)

$CU_{td,t}$ = concentration of copper in sediment at turbine discharge at time t (mg/kg)

$CU_{tr,t}$ = concentration of copper in sediment at tailrace at time t (mg/kg)

$PB_{pi,t}$ = concentration of lead in sediment at power intake at time t (mg/kg)

$PB_{by,t}$ = concentration of lead in sediment at boatyard at time t (mg/kg)

$PB_{td,t}$ = concentration of lead in sediment at turbine discharge at time t (mg/kg)

$PB_{tr,t}$ = concentration of lead in sediment at tailrace at time t (mg/kg)

$CR_{pi,t}$ = concentration of chromium in sediment at power intake at time t (mg/kg)

$CR_{by,t}$ = concentration of chromium in sediment at boatyard at time t (mg/kg)

$CR_{td,t}$ = concentration of chromium in sediment at turbine discharge at time t (mg/kg)

$CR_{tr,t}$ = concentration of chromium in sediment at tailrace at time t (mg/kg)

3.1.2.5.3 Algae constraint

The quantity of algae as a function of nitrate (NO) and phosphate (PO) at any location i in the reservoir at time, t is desired to be more than the WHO and NESREA standards for NO and PO in freshwater (Mohan *et al.*, 2013; FRN, 2011). They are mathematically written as in Equations 36 and 37. The relationship between the monthly

NO and PO with reservoir storage and release were established using linear regression for the selected locations as shown in Equations 38 to 45.

$$NO_{i,t} \geq NO_{std} \tag{36}$$

$$PO_{i,t} \geq PO_{std} \tag{37}$$

$$NO_{pi,\,t} = 0.0002\,\mathrm{S_t} + 8.593 \tag{38}$$

$$NO_{by,\,t} = 0.0002\,\mathrm{S_t} + 8.0218 \tag{39}$$

$$NO_{td,\,t} = 0.0077\,\mathrm{R_t} - 5.6139 \tag{40}$$

$$NO_{tr,\,t} = 0.0043\,\mathrm{R_t} + 1.3201 \tag{41}$$

$$PO_{pi,\,t} = 6\mathrm{E}-05\,\mathrm{S_t} + 0.103 \tag{42}$$

$$PO_{by,\,t} = 5\mathrm{E}-05\,\mathrm{S_t} + 0.2481 \tag{43}$$

$$PO_{td,\,t} = 0.0012\,\mathrm{R_t} - 1.6751 \tag{44}$$

$$PO_{tr,\,t} = 0.0012\,\mathrm{R_t} - 1.6751 \tag{45}$$

where:

$NO_{i,\,t}$ = concentration of NO at location i at time t (mg/l)

NO_{std} = NO standards = 9.1 mg/l (Mohan *et al.*, 2013; FRN, 2011)

$PO_{i,\,t}$ = concentration of PO at location i at time t (mg/l)

PO_{std} = PO standards = 0.5 mg/l (Mohan *et al.*, 2013; FRN, 2011)

$NO_{pi,\,t}$ = concentration of NO at power intake at time t (mg/l)

$NO_{by,\,t}$ = concentration of NO at boatyard at time t (mg/l)

$NO_{tr,\,t}$ = concentration of NO at tailrace at time t (mg/l)

$NO_{td,\,t}$ = concentration of NO at turbine discharge at time t (mg/l)

$PO_{pi,\,t}$ = concentration of PO at power intake at time t (mg/l)

$PO_{by,t}$ = concentration of PO at boatyard at time t (mg/l)

$PO_{tr,t}$ = concentration of PO at tailrace at time t (mg/l)

$PO_{td,t}$ = concentration of PO at turbine discharge at time t (mg/l)

S_t = reservoir storage at time t (Mm^3)

R_t = release at time t (Mm^3)

3.1.2.5.4 Fish population (FP) constraint

Fish yield can be defined as the portion of fish production removed for use by human over a given period (Hortle, 2007). The units of yield are generally kg per capita per year or metric tonnes (Mtonnes) from a given area per year. Fish yield is best indicator of size of fishery, as biological production is impossible to measure in large systems (Hortle, 2007). The mean monthly fish population (FP) data in the Kainji reservoir at time t in term of fish yield was collected from the NIFFR for the period of available record (1994 to 1998) (du Feu and Abiodun 1999). The data was used in the formulation of fish population constraint. The fish population in the reservoir at time t is desired to be more than the optimum fish yield (FP_{opt}). This is mathematically expressed in Equation 46. Miranda *et al.* (2000) studied some characteristics of gill nets and their consequences on fish yield in a reservoir in Brazil. Results revealed that excessive fishing may limit fish yield and commercial value. It was estimated that the optimum sustainable fish yield for all species in the reservoir was 1600 Mtonnes which was adopted in this study. Relationship between the mean monthly FP data with reservoir storage was established using linear regression as shown in Equation 47.

$$FP_t \geq FP_{opt} \tag{46}$$

$$FP_t = 0.1684\,\mathrm{S_t} + 1338.4 \tag{47}$$

where:

FP_t = fish population in the reservoir at time t (Mtonnes)

FP_{opt} = optimum fish population in a reservoir = 1600 Mtonnes (Miranda *et al.,* 2000)

S_t = reservoir storage at time t (Mm^3)

3.2 Reservoir optimization model solution

The formulated model for the hydropower reservoir operation system considering ecological integrity and to determine other associated parameters, LINGO version 17.0 software was used.

4.0 Results and Discussions

4.1 Statistical analysis of hydropower reservoir operation parameters

Results of the monthly variations in hydropower reservoir operation parameters at the station using time plots are presented in Figures 3 to 9. The results of monthly descriptive statistics of operation parameters at the Kainji hydropower station are presented in Tables 3 to 9. The results of the monthly variations of the reservoir operation, water and sediment quality parameters with fish yield using trend analysis are presented in Figures 10 to 16.

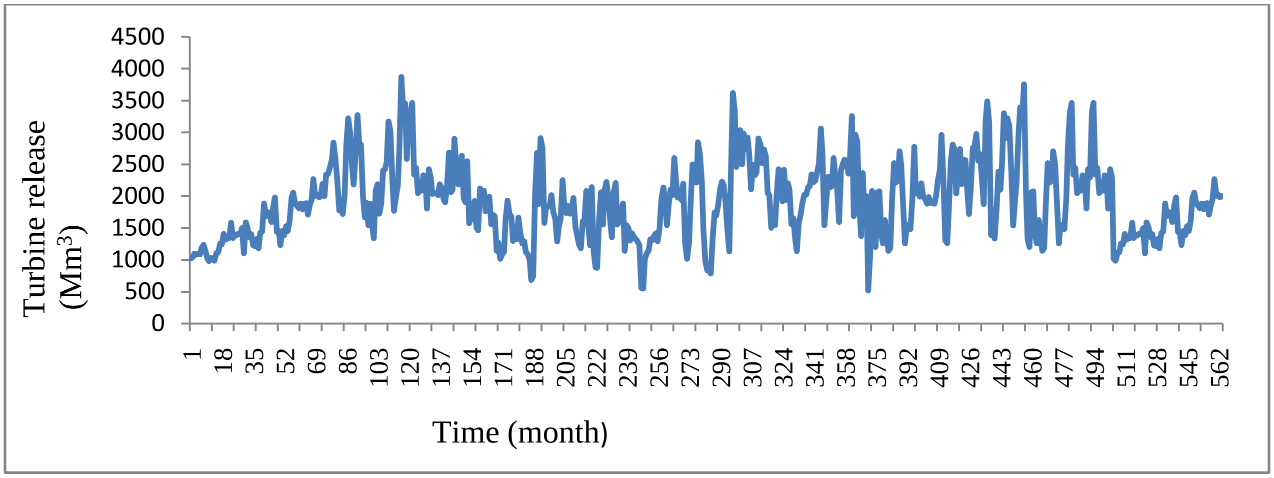

Figure 3: Time plot of turbine releases (Mm^3) at the station (1970-2016)

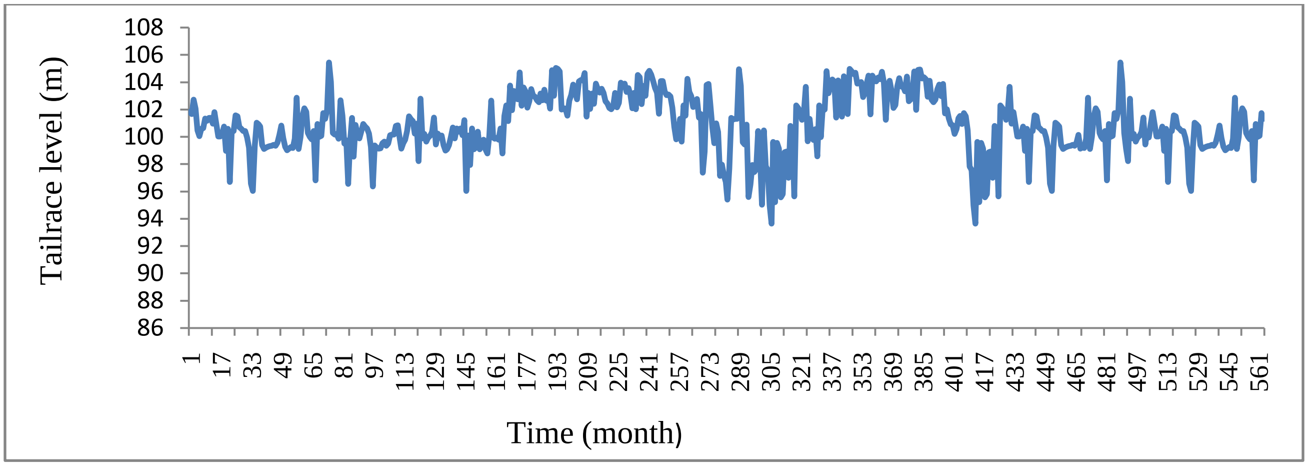

Figure 4: Time plot of tailrace level (m) at the station (1970-2016)

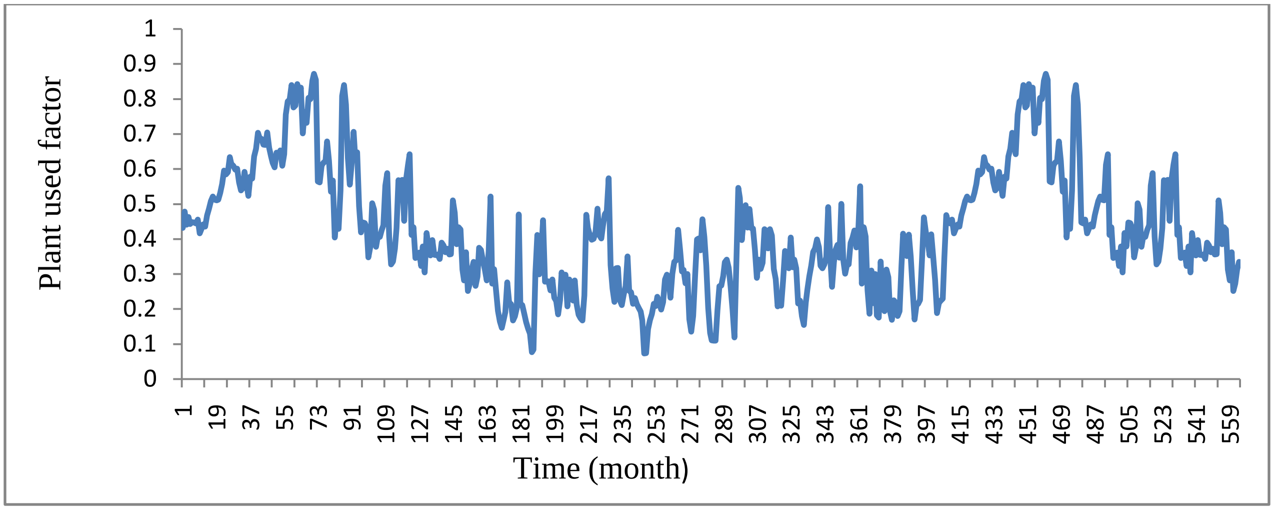

Figure 5: Time plot of plant use coefficient at the station (1970-2016)

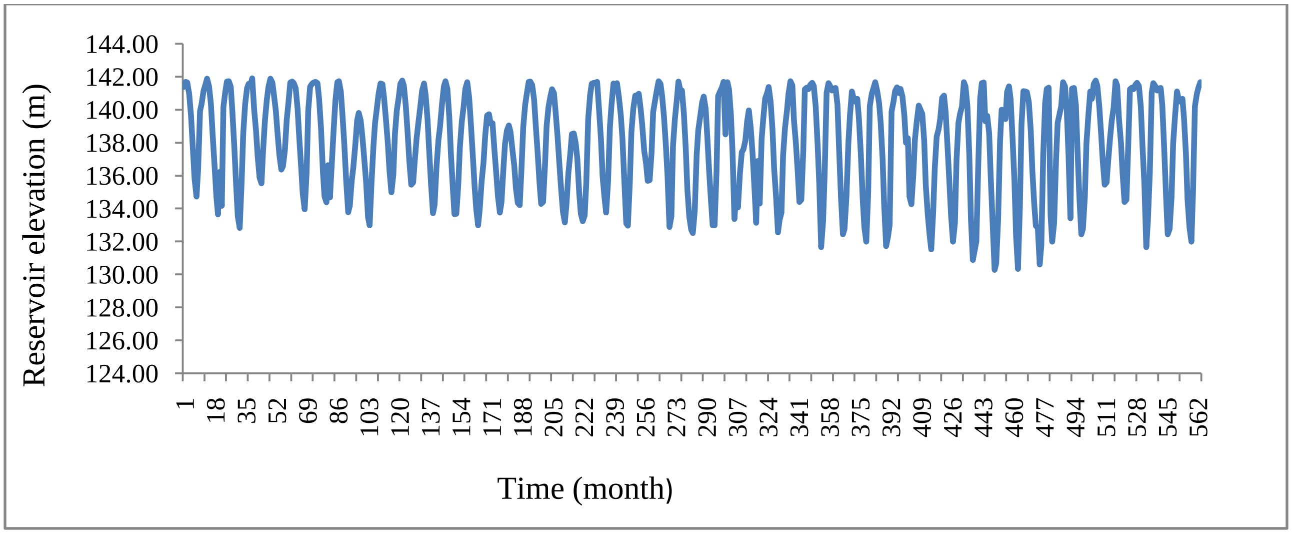

Figure 6: Time plot of reservoir elevation (m) at the station (1970-2016)

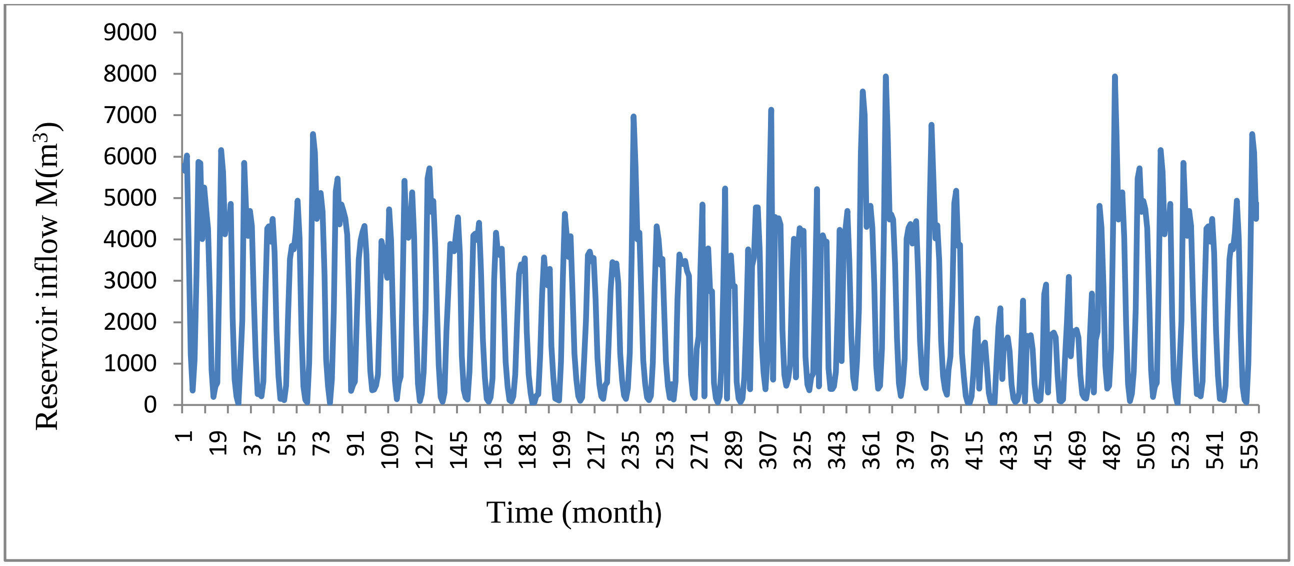

Figure 7: Time plot of reservoir inflow (Mm^3) at the station (1970-2016)

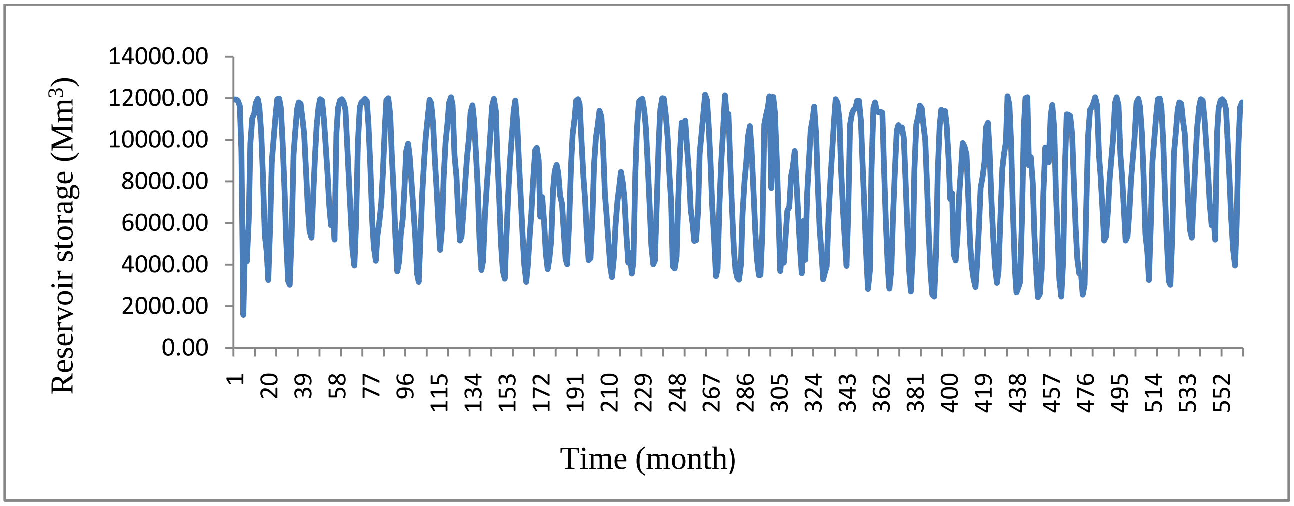

Figure 8: Time plot of reservoir storage (Mm^3) at the station (1970-2016)

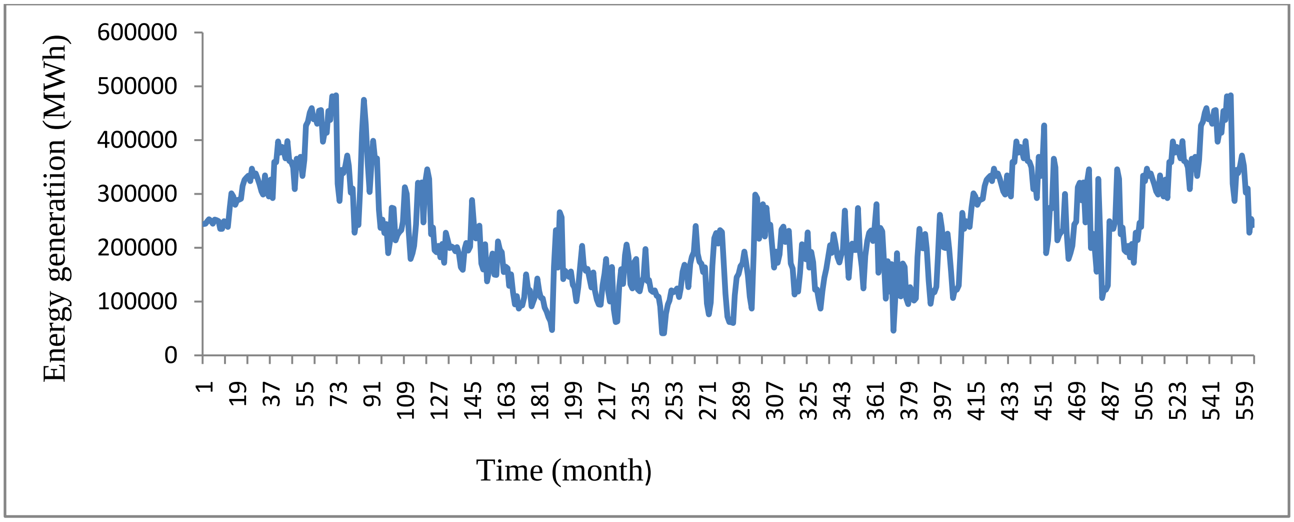

Figure 9: Time plot of energy generation (MWh) at the station (1970-2016)

Table 4: Monthly descriptive statistics of turbine release from Kainji lake (Mm^3) (1970-2016)

Month	Min	Max	Mean	Median	Std Dev
Jan	1009.9	3306.3	2100.29	2059.645	623.90
Feb	980.3	3464.2	1968.67	1969.95	652.52
Mar	1082.8	3223.2	2003.06	2012.94	626.94
Apr	1078.7	3486.8	2057.79	2077.45	601.71
May	1084.2	3150.1	1929.54	1956.15	523.76
Jun	874.3	2661.0	1726.74	1799.49	444.09
Jul	552.9	2839.1	1692.75	1744.55	530.30
Aug	544.6	3871.2	1899.93	1830.7	688.81
Sep	779.2	3620.0	1934.42	1877.1	672.48
Oct	1018.4	3452.5	2016.78	1876.95	675.76
Nov	513.9	3237.2	1919.37	1918.005	541.19
Dec	1025.2	3754.9	2053.51	1997.8	622.88

Table 5: Monthly descriptive statistics of tailrace level (m) (1970-2016)

Month	Min	Max	Mean	Median	Std Dev
Jan	95.01	105.04	101.77	101.90	2.46
Feb	96.04	105.44	102.08	101.98	2.08
Mar	97.01	104.79	101.43	101.13	2.33
Apr	97.57	104.75	100.98	100.69	1.98
May	94.92	104.40	100.94	100.51	2.08
Jun	93.64	104.72	100.29	100.21	2.46
Jul	95.41	103.65	100.61	100.57	1.92
Aug	95.22	104.52	101.39	101.43	2.22
Sep	97.42	104.79	101.58	101.55	2.01
Oct	96.04	104.25	101.02	101.25	1.96
Nov	95.56	104.96	101.76	101.73	2.09
Dec	95.80	104.93	101.57	101.44	2.21

Table 6: Monthly descriptive statistics of plant used coefficient (1970-2016)

Month	Min	Max	Mean	Median	Std Dev
Jan	0.20	0.78	0.42	0.42	0.13
Feb	0.17	0.84	0.43	0.41	0.17
Mar	0.15	0.84	0.40	0.38	0.17
Apr	0.16	0.83	0.41	0.37	0.16
May	0.15	0.70	0.38	0.34	0.16
Jun	0.13	0.78	0.36	0.31	0.17
Jul	0.07	0.73	0.33	0.29	0.19
Aug	0.07	0.80	0.35	0.33	0.19
Sep	0.11	0.80	0.37	0.32	0.19
Oct	0.18	0.85	0.39	0.35	0.18
Nov	0.18	0.87	0.39	0.36	0.16
Dec	0.18	0.86	0.42	0.41	0.15

Table 7: Monthly descriptive statistics of reservoir elevation level (m) (1970-2016)

Month	Min	Max	Mean	Median	Std Dev
Jan	138.5	141.9	140.88	141.21	0.94
Feb	138.0	141.9	140.85	141.37	0.99
Mar	136.3	141.9	139.94	140.08	1.41
Apr	134.2	141.1	138.27	138.22	1.79
May	133.0	139.6	136.37	136.43	1.95
Jun	130.3	138.3	134.52	134.52	2.12
Jul	130.3	136.9	133.79	133.74	1.63
Aug	131.8	137.8	134.50	134.25	1.43
Sep	134.0	141.2	137.39	137.07	1.92
Oct	134.2	141.6	139.00	139.41	1.87
Nov	136.5	141.7	140.00	140.36	1.47
Dec	137.8	141.7	140.58	140.98	1.12

Table 8: Monthly descriptive statistics of reservoir inflow (Mm^3) (1970-2016)

Month	Min	Max	Mean	Median	Std Dev
Jan	1255.19	5777.31	3687.34	3668.07	400.43
Feb	678.71	5660.93	2855.49	2667.17	479.17
Mar	218.42	6029.08	1436.97	778.09	392.84
Apr	33.70	3641.76	527.13	265.09	214.94
May	36.06	1218.67	239.24	166.06	71.68
Jun	24.36	1353.02	322.48	225.50	89.47
Jul	259.81	2319.49	906.91	807.92	137.40
Aug	1218.67	6071.93	2741.95	2611.44	320.89
Sep	2091.83	7944.48	4704.89	4250.88	515.77
Oct	78.00	7009.37	3582.43	3788.60	711.80
Nov	1323.83	4668.19	3609.45	3741.55	293.82
Dec	1413.58	5255.02	3878.84	4123.40	335.34

Table 9: Monthly descriptive statistics of reservoir storage (Mm^3) (1970-2016)

Month	Min	Max	Mean	Median	Std Dev
Jan	7675.1	12089.7	10951.2	11364.0	1186.00
Feb	7929.4	12069.2	10886.2	11394.6	1231.53
Mar	5776.0	12000.0	9898.0	10336.6	1676.32
Apr	4302.2	11229.3	8069.6	8347.9	1895.62
May	3587.5	9262.7	6425.0	6641.0	1691.91
Jun	2432.4	7628.6	4714.3	4787.0	1468.20
Jul	2450.6	6107.4	4000.7	3840.2	1045.49
Aug	2458.0	6954.9	4245.3	4102.0	1045.49
Sep	3941.3	10735.5	6608.2	6333.2	1667.93
Oct	5135.3	11541.2	8811.0	8885.7	1746.30
Nov	6184.8	12138.3	9913.3	10392.0	1680.25
Dec	7557.3	12173.0	10580.4	10952.4	1328.05

Table 10: Monthly descriptive statistics of energy generation (MWh) (1970-2016)

Month	Max	Min	Mean	Median	Std Dev
Jan	441609.0	110481.0	236067	236553	76687.66
Feb	430537.0	87243.0	216262	201920	84748.07
Mar	474970.0	92769.0	222673	206200	95539.56
Apr	455818.0	89184.0	221619	195211	89500.28
May	398070.0	81751.0	207800	192405	89958.13
Jun	416966.0	62140.0	191429	164349	93007.59
Jul	413902.0	41407.0	180177	145619	105258.72
Aug	454048.0	41653.0	193323	168801	108583.54
Sep	437760.0	60243.2	197388	160529	104737.45
Oct	481755.0	94262.0	213806	193023	102017.97
Nov	477158.0	46433.0	209940	191561	93284.19
Dec	483451.0	94922.0	228975	213565	85710.14

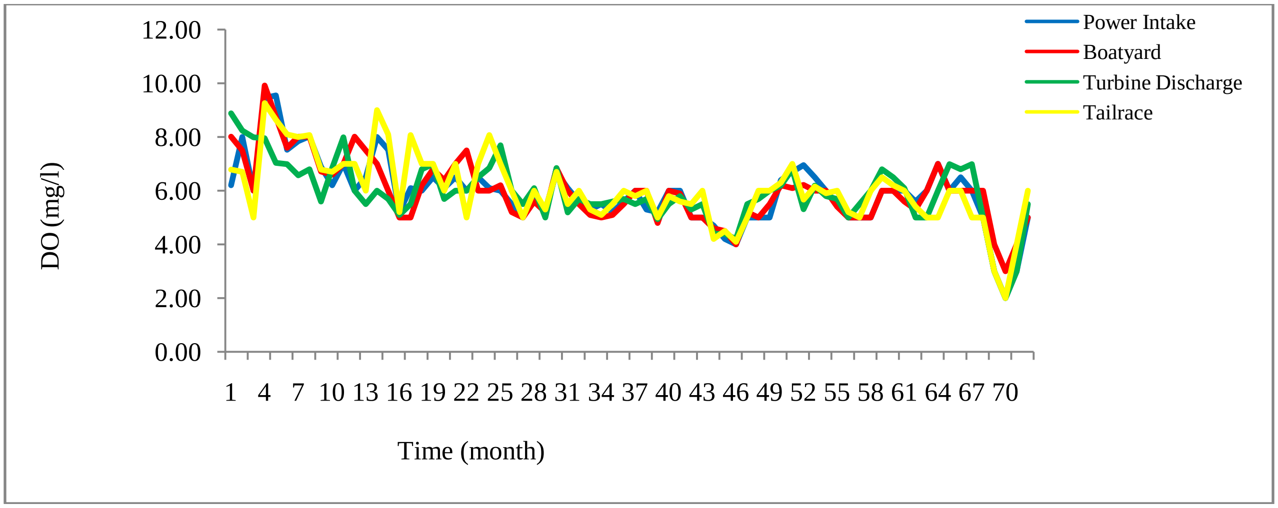

Figure 10: Time plot of DO concentration (mg/l) in water at selected locations

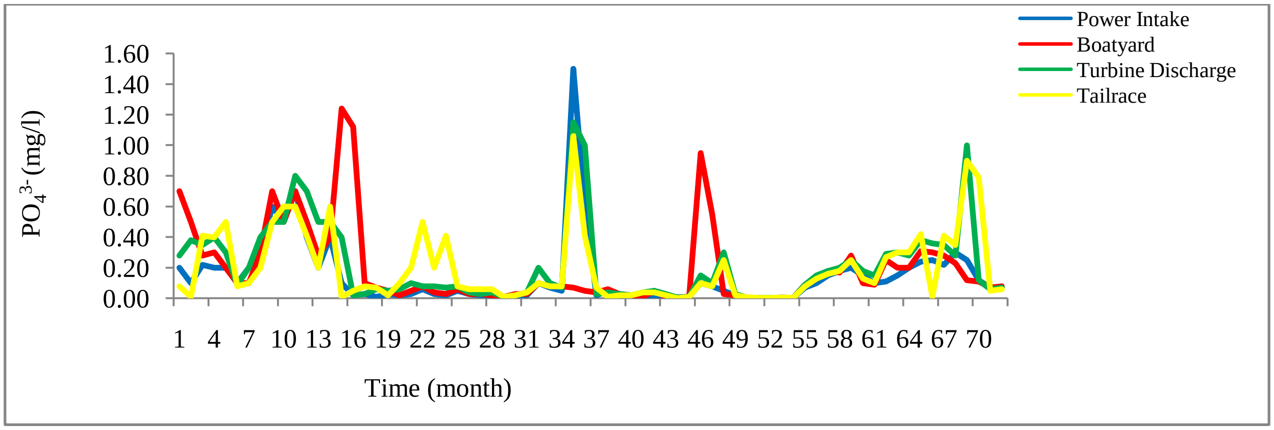

Figure 11: Time plot of PO_4^{3-} concentration (mg/l) in water at selected locations

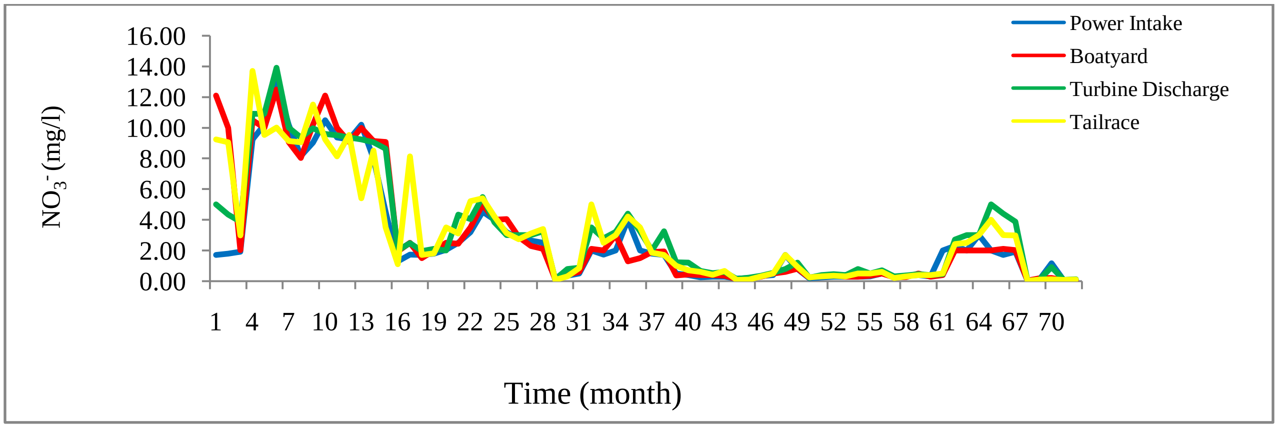

Figure 12: Time plot of NO_3^- concentration (mg/l) in water at selected locations

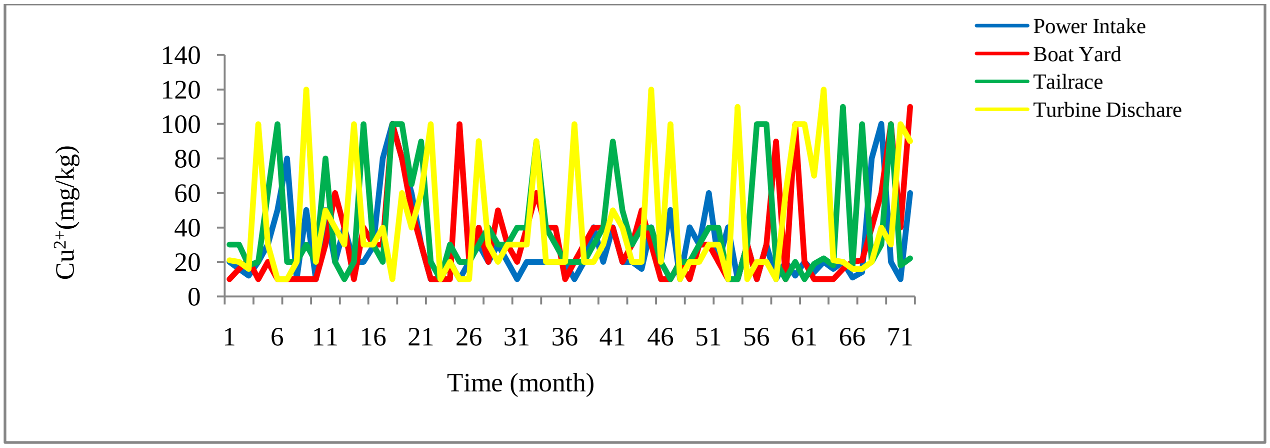

Figure 13: Time plot of Cu^{2+} (mg/kg) in sediment at selected locations

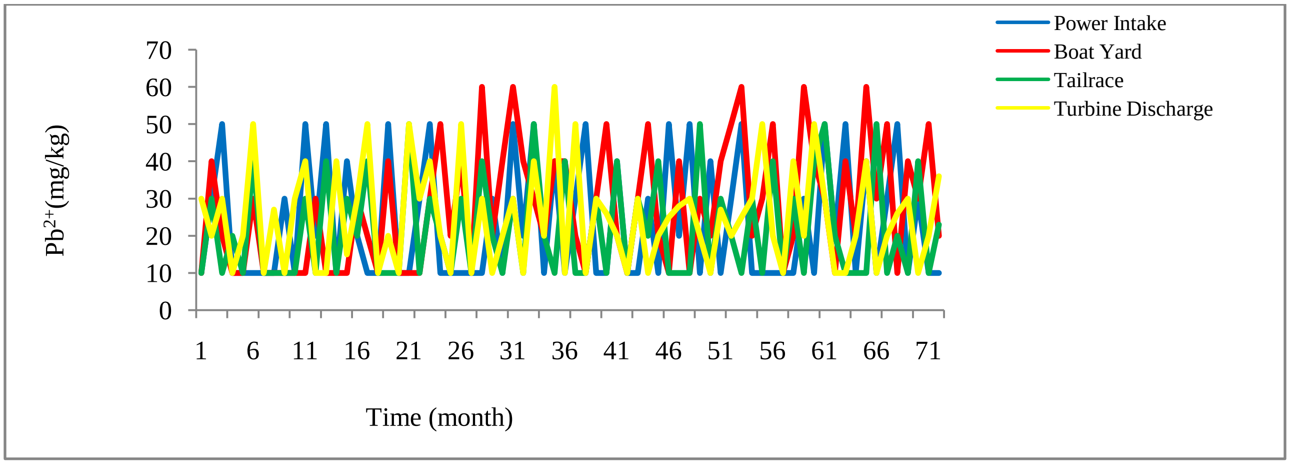

Figure 14: Time plot of Pb^{2+} (mg/kg) in sediment at selected locations

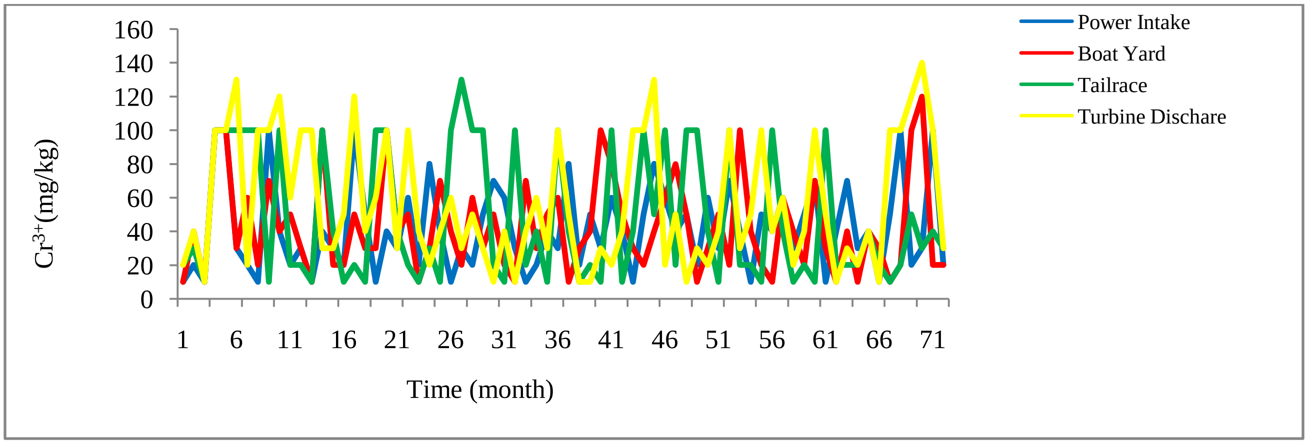

Figure 15: Time plot of Cr^{3+} (mg/kg) in sediment at selected locations

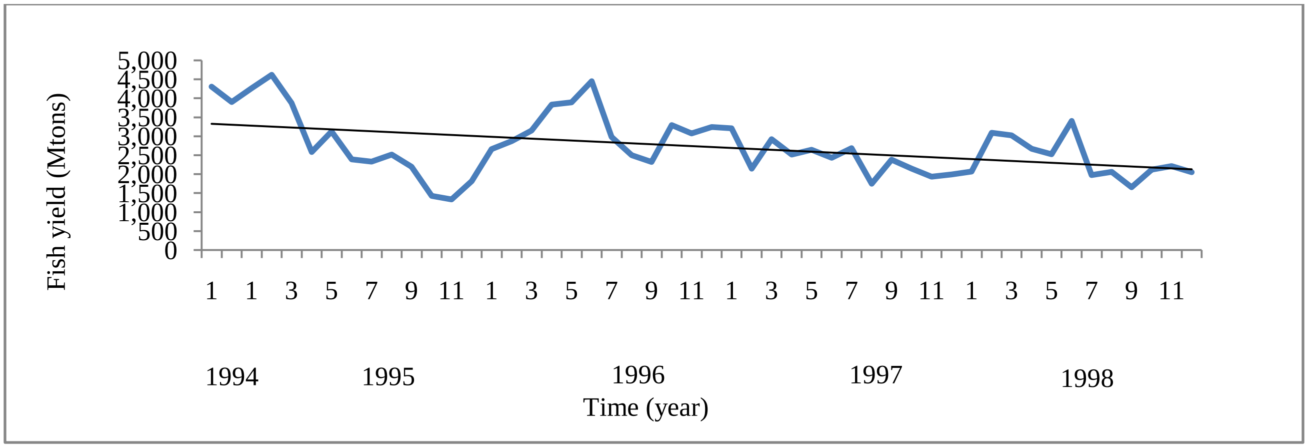

Figure 16: Time plot of Fish Yield at Kainji Lake

4.2 Reservoir operation optimization

The total optimum annual energy generation of 2565.892 GWh was obtained for the mean monthly hydropower reservoir operation at the Kainji station. The optimum results for other reservoir operation parameters are presented in Table 10. The optimum results for the ecological integrity indicators vary between: 5.7 to 7.2 mg/l, 9.5 to 11.5 mg/l and 0.5 to 0.99 mg/l for DO, NO_3^- and PO_4^{3-} concentration respectively in water. The optimum results for the ecological integrity indicators using sediment quality range between 27.9 to 68.6 mg/kg, 21.9 to 33.4 mg/kg and 40.1 to 95.0 mg/kg for Cu^{2+}, Pb^{2+} and Cr^{3+} concentration respectively in sediment. The optimum fish yield varies between 2583 to 3141 Mtonnes.

Table 11: Optimized mean monthly hydropower operation parameters

Time (month)	H (m)	R (Mm^3)	S (Mm^3)
Jan	40.64	2217.88	10707.22
Feb	40.38	2217.88	10441.80
Mar	40.64	2217.88	10707.22
Apr	39.55	2217.88	9593.21
May	37.69	2217.88	7698.61
Jun	40.64	2217.88	10707.22
Jul	38.72	2217.88	8748.51
Aug	37.39	2217.88	7391.20
Sep	37.83	2217.88	7854.23
Oct	40.05	2217.88	10105.59
Nov	40.64	2217.88	10707.22
Dec	40.64	2217.88	10707.22

4.3 Discussion of Results

4.3.1 Reservoir operation statistics

The monthly variations in hydropower operational parameters using time series trend analysis revealed that all the variables varied with time. Trend of mean monthly plant used coefficient and turbine release (Mm^3) followed similar pattern with the energy generation (MWh) (Figures 3, 5 and 9) respectively. Variation in mean monthly reservoir storage with elevation level in Figure 4.8 revealed that there is very strong positive relationship in the variables with R^2 of 0.99. The mean turbine release varied between 1692.75 to 2100.29 Mm^3 (Table 4). The mean tailrace level ranged between 101.02 and 102.08 m (Table 5). The mean monthly energy generation was found between 180177.00 and 236067.00 MWh (Table 10).

4.3.2 Reservoir operation optimization

The total optimal annual energy generation of 2565.892 GWh was found to be higher than the actual total annual energy generation of 2519.459 GWh. This implies that the total annual energy generation will increase by 1.84%. This will improve the total energy that will be made available to the national grid from the Kainji hydropower station without compromising the ecological integrity of the reservoir.

The optimum reservoir operation head, H (m) shown in Table 10 indicated that H vary between 37.39 to 40.64 m, which fell within the limit of 33 to 41 m from the observed historical data. The turbine release, R (Mm^3) (Table 11) revealed that there was constant value of R of 2217.88 Mm^3 for the months, which fell with the range of 500 to 3900 Mm^3 from the observed historical data. Also, the reservoir storage, S (Mm^3) (Table 11) showed that the S varied between 7391.2 to 10707.22 Mm^3, this implies that the optimized storages are within the limit of 3000.00 to 12000.00 Mm^3 observed in the actual operation of the Kainji hydropower reservoir.

The optimized DO concentration in water at the four sampling locations revealed that the DO varies between 5.7 to 7.2 mg/l, which is higher than the minimum DO standard of 5.0 mg/l for freshwater, fish and other aquatic animals as per WHO and NESREA standards (Mohan *et al.*, 2013; FRN, 2011). It can be inferred that optimizing the reservoir operation will increase total energy and also improve the DO content in water.

The optimized NO_3^- and PO_4^{3-} concentration (as function of algae) in water at the four sampling locations revealed that the NO_3^- and PO_4^{3-} vary between 9.5 to 11.5 mg/l and 0.5 to 0.99 respectively. These are greater than the minimum NO_3^- standard of 9.1 mg/l and greater than 0.5 mg/l for PO_4^{3-} in water as specified in WHO and NESREA standards (Mohan *et al.*, 2013;

FRN, 2011). This will favour the growth of algae in the reservoir which is one of the key indicator for ecological health of a reservoir (Sharma and Sharma, 2003).

The optimized Cu^{2+}, Pb^{2+} and Cr^{3+} concentration in sediment at the four sampling locations shown in Tables 6 to 8 indicated that the Cu^{2+}, Pb^{2+} and Cr^{3+} vary between 27.9 to 68.6 mg/kg, 21.9 to 35.0 mg/kg and 39.7 to 95 mg/kg respectively. These fell within the limits of 80, 35 and 95 mg/kg SQG standards respectively for Cu^{2+}, Pb^{2+} and Cr^{3+} heavy metal concentration in sediment in freshwater as proposed by WDOE (Easthouse, 2009). This will not impact negatively on the aquatic habitats in the reservoir.

The optimized fish yield, FP (Mtonnes) in the reservoir revealed that the FP ranges between 2583 to 3141 Mtonnes which is higher than the optimum fish yield (FP_{opt}) of 1600 Mtonnes (Miranda *et al.*, 2000). It can be inferred that optimizing the reservoir operation will increase total energy and also ensued the availability of fish present in the reservoir.

6.0 Conclusion

This study focused on the optimization of energy generation using operations and ecological integrity constraints. Linear optimization technique was adopted in optimizing average total annual energy generation subject to operation and ecological integrity constraints. The model was solved with LINGO 17.0 software. Results revealed that the optimization approach will increase the total annual energy generation at Kainji station by over 1%. This will improve the availability of electricity to consumer in Nigeria. Also, it was observed that ecological integrity indicators were satisfactory as compared to various standards used in the study.

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