Optimization-based reliability of a multipurpose reservoir by Genetic Algorithms: Jebba Hydropower Dam, Nigeria

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Abstract: This study is focused on the application of Genetic Algorithm (GA) as an effective tool for modeling the operation of a multi-purpose reservoir with specific emphasis on Jebba Hydropower Dam, Nigeria. The specific objectives are to study the reservoir operation rule; model the reservoir parameters such as inflow, elevation, turbine release, generating head, energy generation, tailrace water level and plant coefficient. Available Data for 27-year period (1984–2011) was obtained from the Dam Station for statistical analysis. MATLAB software for GA was used, and for comparison and check, another similar optimization software (LINGO) was utilized. The optimal solution obtained at operating performance of 50% reservoir inflow reliability has total annual energy generation of 42,105.63 MWH. GA for the total annual energy generation at operation performance of 95, 90 and 75% reservoir inflow reliability are 15,964.48 MWH, 21,009.53 MWH and 20,798.58 MWH, respectively. The application of GA will lead to a more realistic and reliable optimal value for the improvement of hydroelectric power generation and flood management, which would guide decision makers in the hydropower sector.

Subjects: Civil, Environmental and Geotechnical Engineering; Water Engineering; Hydraulic Engineering

Keywords: reservoir operation; Jebba Hydropower Dam; flood management; optimization; Genetic Algorithm; LINGO

ABOUT THE AUTHORS

The focus of the research group is in the area of Civil, Water Resource and Environmental Engineering. The research interest includes: Hydraulics and Hydrological Studies, Water Supply in rural and urban communities, Modeling, Simulation and Optimization of Waste water Treatment System, Solid Waste Management, WaSH in Schools program, Rural/Urban Sanitation and Hygiene studies, and Waste-to-Wealth. The research is related to water resources management and to guide decision makers in the hydro-power sector.

PUBLIC INTEREST STATEMENT

This study is focused on the application of an effective tool for modeling the operation of a multi-purpose reservoir. Analysis was performed on the available 27-year data (1984–2011) obtained from Jebba Hydropower Dam, Nigeria. The specific objectives are to study the reservoir operation rule; model the reservoir parameters such as inflow, elevation, turbine release, generating head, energy generation, tailrace water level and plant coefficient. The optimal solution obtained at operating performance of 50% reservoir inflow reliability has total annual energy generation of 42,105.63 MWH. The application of this tool will lead to a more realistic and reliable optimal value for the improvement of hydroelectric power generation and flood management, which would guide decision makers in the hydropower sector.
1. Introduction

Jebba Hydropower Dam (JHD) has been performing below 30% of power efficiency (Jimoh, 2009). This is because hydrological issues such as inter-annual and seasonal variations in inflow to the reservoir affect the volume of water available for operating the turbines (Mythili, Devi, Raviteja, & Kumar, 2013). Sometimes, the water volume in the reservoir is low. At other times, the reservoir is full without sufficient capacity to receive high inflow during the peak of rainy season in August or September, which results in flooding of downstream section of the reservoir (Olukanni, Adejumo, Adedeji, & Salami, 2016; Olukanni & Salami, 2008, 2012). Despite the hydrological challenges, the JHD is expected to generate electricity at pre-determined level throughout the year, and control downstream flooding for economic, environmental and social benefits. The initial goal requires water level in the reservoir to be as high as possible, while the latter objective requires the water level to be low prior to the arrival of high inflow. However, there is conflict between these two objectives during the pre-flooding season. Most reservoir are presently for multiple purposes, which includes drinking water supply, hydropower, irrigation, aquaculture, low-flow augmentation, navigation etc. Nagesh Kumar, Baliarsingh, and Srinivasa Raju (2010) expressed that multipurpose flood control reservoir is more difficult to operate because it requires an optimized operation to maximize its benefits.

Reservoir Operation (RO) has the potential to alter flow regimes, fix river shape or separate river channels from its flood plains under new flow and sediment regimes (Olukanni & Salami, 2012). The need for sustainable development has brought to light the importance of addressing the negative consequences of flood control and protective measures on natural flow regimes that have the potential to threaten human security, including life and livelihoods, food and health security (Bosona & Gebresenbet, 2010). In the case of a reservoir built for flood control, a consistent relationship between impoundment and change in flow variables can be expected (Batalla, Gómez, & Kondolf, 2004). However, for a reservoir built for irrigation and hydropower generation, the relation is expected to be strident because flood reduction normally would not be the main purpose (Walker, 1985). In many cases, the purposes of flood control and hydropower generation requirement are regarded as being important in the determination of control strategies for reservoirs.

RO is a complex problem that involves numerous hydrological, technical, economical, environmental, institutional and political considerations (Mythili et al., 2013). It also involves many decision variables, multiple objectives as well as considerable risk and uncertainty (Reddy & Kumar, 2006). In addition, the conflicting objectives lead to significant challenges for operators when making operational decisions; hence its operation can involve complicated hydrologic, environmental and economic constraints with conflicting management objectives (Wang, Yuan, & Zhang, 2004). Traditionally, reservoir operation is based on heuristic procedures, embracing rule curves and subjective judgments by the operator. In this case, general operation strategies are provided for reservoir releases according to the current reservoir level, hydrological conditions, water demands and the time of the year (Olukanni et al., 2016). Established rule curves, however, do not allow a fine-tuning (and hence optimization) of the operations in response to changes in the prevailing conditions. Therefore, it would be valuable to establish an analytical and more systematic approach to reservoir operation. This is not based only on traditional probabilistic/stochastic analysis, but, also on the information and prediction of extreme hydrologic events and advanced computational technology in order to increase the reservoir’s efficiency for balancing the demands from the different users (Olukanni et al., 2016).

Many mathematical models have been developed; however, researchers are still not fully satisfied with them as new problems such as high dimensionality are coming up (Mathur & Nikam, 2009; Otti & Nwafor, 2012). Applying optimization techniques for reservoir operation is not a new idea. Various techniques have been applied in an attempt to improve the efficiency of reservoir(s) operation. The choice of techniques usually depends on the reservoir specific system characteristics, data availability, the objectives specified and the constraints imposed (Bosona & Gebresenbet, 2010). Mathur and Nikam (2009) in a state of art review on optimal operation of multi-reservoir system highlighted...
different optimization models suitable for high-dimensional, dynamic, nonlinear and stochastic characteristic of reservoir system. These techniques include Dynamic Programming (DP) (Otti & Nwoafor, 2012); Stochastic Dynamic Programming (SDP) (Liu, Zhao, Li, & Shen, 2012; Mythili et al., 2013) and Heuristic Programming such as Genetic algorithms (GA) (Ghadami, Ghahraman, Sharifi, & Mashhadi, 2009; Karamouz, Abesi, Moridi, & Ahmadi, 2009), Shuffled Complex Evolution, Fuzzy logic, and Neural Networks etc. (Long, 2006; Wei & Hsu, 2008). In spite of extensive research in reservoir optimization, researchers are still in search of new optimizing techniques, which can derive more efficient reservoir operating policy for reservoir operation.

Furthermore, many of the aforementioned techniques have been implemented in realistic scenarios, and many reservoir systems worldwide are operated based on the decision rules generated from these techniques. However, there exists a gap between theory and practice, and full implementation has not been achieved yet (Labadie, 2004). The use of Genetic Algorithm in determining the optimal reservoir operation policies, is receiving significant attention from water resources engineers. One of its advantages is that it identifies alternative near optimal solutions and can be used in identifying effective operation policies and solving problems in water resource development (Ahmed & Sarma, 2005; Akoshile & Olaoye, 2009; Alireza, Sedghi, Fahmi, & Musavi, 2010; Mathur & Nikam, 2009). Genetic Algorithm as a technique can be applied to solve variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, non-differential, stochastic or highly non linear. The technique is an effective search method for modeling the operation policy of a multipurpose reservoir which leads to a more realistic and reliable optimal value for the improvement of hydroelectric power generations and flood management.

The Genetic Algorithm is one such optimizing technique that is robust and is considered in this study for deriving multipurpose reservoir operating policies. The basic difficulty a reservoir manager faces is to take a real-time optimum decision regarding releases according to the future demand and inflow. The focus of this study is to apply effective search method for modeling the operation policy of a multi-purpose reservoir. The objectives are to: (i) study the present reservoir operating rule; (ii) model the reservoir parameters such as (inflow, elevation, turbine release, generating head, energy generation, tailrace water level and plant coefficient); and (iii) solve the problem using Genetic Algorithm.

2. Methodology

2.1 Description of study area

Jebba Hydroelectric Power Station is along River Niger, Nigeria, located between latitudes 9° 10’ N to 9° 55’ N and longitudes 4° 30’ E to 5° 00’ E at 76 m above sea level (about 100 km downstream of Kainji dam). The station is still one of the most cost-effective sources of electricity in Nigeria. It has maximum length of 100 km (km), maximum depth of 32.5 km, maximum width of 10 km and a mean depth of 3.3 m. The surface area is 350 km², maximum volume of 1,000 × 10⁶ m³, operating head of 27.6 m and maximum flow per unit of 380 m³/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. All the turbines are connected in the switchyard through 330 kV switch gears into 330 kV bus-bars “A” and “H” with tow outgoing lines B8 J and B9 J to Jebba Transmission switch yard (Goldberg, 1989). The dam was developed and constructed in 1979 and there has been no overhaul of the dam in twenty-five years. However, routine minor and major repair works, and preventive maintenance have been carried out Figure 1. This has kept the station performance well above average. Figures 2 and 3 show the locations of River Niger Basin and that of Jebba dam.
2.2. Optimization models

Optimization models are based on clearly defined goals (objective functions), criteria for evaluation of control decisions, and constraints as limitations during optimization. John (2004) expressed that in reservoir optimization models, objective functions such as efficiency (i.e. maximizing current and future discounted welfare), survivability (i.e. assuring future welfare exceeds minimum subsistence levels), and sustainability (i.e. maximizing cumulative improvement over time) should be incorporated. The criteria are economic, social and environmental issues. The typical constraints in a reservoir optimization model, (including conservation of mass and other hydrological and hydraulic constraints, minimum and maximum storage and release, hydropower and water requirements as well as hydropower generation limitations) are presented in Equations (1)–(5) as adapted from Long (2006) and with reference to John (2004):

![Figure 1. The River Niger Basin. Source: Ifabiyi (2011).](image1)

![Figure 2. Location of Jebba Hydropower Dam on Nigeria map.](image2)
(a) Hydraulic constraints are defined by the reservoir continuity equation.

\[
S_{(t+1)} = S_{(t)} + I_{(t)} - R_{(t)} \quad t = 1, 2, 3 \ldots T
\]  

where: \(S_{(t+1)}\) is storage at time step \(t+1\); \(S_{(t)}\) is storage at time step \(t\); \(I_{(t)}\) is the reservoir net inflow at time step \(t\) (including reservoir inflow, precipitation and evaporation); \(R_{(t)}\) is the reservoir outflow at time step \(t\). \(T\) is the total number of time steps in the considered period.

(b) Constraints on discharge are defined by maximum and minimum permissible reservoir releases:

\[
R_{\text{min}} \leq R_{(t)} \leq R_{\text{max}} \quad t = 1, 2, 3, \ldots T
\]  

(c) Constraints on storages are defined by maximum and minimum permissible reservoir storages:

\[
S_{\text{min}} \leq S_{(t)} \leq S_{\text{max}} \quad t = 1, 2, 3, \ldots T
\]  

(d) Constraints on elevations are defined by maximum and minimum permissible water level at specified sites:

\[
h_{\text{min}} \leq h_{(t)} \leq h_{\text{max}} \quad t = 1, 2, 3, \ldots T
\]  

(e) Constraints on hydropower generations are defined by maximum capacity and minimum requirement of hydroelectricity:

\[
HP_{\text{min}} \leq HP_{(t)} \leq HP_{\text{max}} \quad t = 1, 2, 3, \ldots T
\]  

\(HP(t)\) is a nonlinear function of \(S(t)\) and \(R(t)\).

Optimization problems can generally be either single-objective or multi-objective. The main concern of single-objective optimization is to define the minimum or maximum value of an objective function, depending on the goal. The single-objective is just measuring the goal of operation of a single-purpose reservoir, or it may weigh different objectives using a fixed set of weights for operation of a multi-purpose reservoir. It can provide operators with direct decisions for reservoir operations.
operation. However, in most cases operation objectives have trade-offs, and hence single-objective optimization cannot provide a unique optimum solution. In such situations improvement of some objectives cannot be achieved without the sacrifice of others. The goal of the single-objective analysis should be replaced by the concept of “non-inferiority” in the multi-objective analysis (Mays & Tung, 2002). An operation decision based on the solution of a multi-objective optimization problem requires that the operator expresses his/her preference by choosing the most suitable solution in the set of optimal solutions. Multi-objective optimization refers to problems with several objectives that are expected to be fulfilled simultaneously. The objectives are however often in conflict with each other and measured by different units. Equations 6 and 7 show in general, a formulated multi-objective reservoir operation problem:

\[
\text{Minimize } F(X) = [F_1(X), F_2(X), \ldots, F_N(X)]
\]  

(6)

Subject to \[ q_i(X) \leq 0 \quad i = 1, 2, \ldots, m \]

(7)

where \( F_j(X), j = 1, \ldots, N \) are the objective functions.

\( X \) is a vector of decision variables.

\( q_i(X) \) are constraints that define the feasible of solutions.

A number of techniques to solve multiple objective function optimization problems have been presented in the literature. They can be classified into two main groups:

(i) aggregation approaches;

(ii) Pareto domination approaches.

In the first approach, the priorities of the objectives are established, whereas in the second approach, no preference information is considered or is available before the search (Burke & Landa-Silva, 2006).

2.3. Formulation of reservoir operation problem

2.3.1. System and problem description

The reservoir arrangement and Bacita irrigation projects is shown in Figure 3 while the basic data on hydropower system is given in Table 1. The section under consideration has four flow gauge sites (at sites 1, 3, 4, and 5) a flood prone area at site 6, hydropower reservoir (at sites 2), and an irrigation projects at site 7.

| Table 1. Basic data on the Jebba hydropower system |
|-----------------------------------------------|
| **First year of operation** | **1,984** |
| Installed capacity (MW) | 540 |
| Design power plant factor | 0.70 |
| No. of generators | 6 |
| Reservoir flood storage capacity (Mm³) | 4,000 |
| Reservoir flood level (m) | 103.55 |
| Water Surface Area (Km²) 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 (Mm³)(active storage capacity) | 3,880 |
| Minimum storage (Mm³)(Dead storage capacity) | 2,880 |

Source: Power holding company of Nigeria (PHCN) 2012.
Figures 4 and 5 show a model flowchart and the reservoir operation flowchart, respectively.

The optimal monthly releases from the reservoirs are determined subject to various constraints. Maximization of energy output is considered as the objective function, while reservoir characteristics, the irrigation requirements and flood control are included in the constraints.

2.3.2. Objective function

The objective function is:

Maximize the annual energy generation for the Jebba hydropower plants. Using the numbering system in Figure 3 (2 stands for Jebba), this gives:

\[
Z = \text{Max} \sum_{t=1}^{12} (E_{2t})
\]  \( \text{(8)} \)

where:

\[ Z \] is total annual energy generation (MWH)

\[ E_{2t} \] is monthly energy generation at Jebba H.P dam (MWH)

Energy can be calculated as shown in Equation (9) as

\[
E = 2.73R_{2t}H_{2t}^\epsilon \text{(MWH)}
\]  \( \text{(9)} \)

Then, the objective function becomes

\[
Z = \text{Max} \sum_{t=1}^{12} (2.73 R_{2t} H_{2t}^\epsilon)
\]  \( \text{(10)} \)

Furthermore, the generating head \( (H_{2t}^\epsilon) \) in Equation (10) can be expressed in terms of reservoir storage and minimum operating reservoir elevation as given in Equation (11), which on substituting in Equation (10) will give Equation (12).
where:

\[ H_{2t} = H_{rf}(S_{2t}) - H_{min.2t} \]  \hspace{1cm} (11)

\[ Z = \text{Max} \sum_{i=1}^{12} 2.73 \left\{ \left( R_{2t} \left( \left( H_{rf}(S_{2t}) - H_{min.2t} \right) \right) \right) \right\} \varepsilon_2 \]  \hspace{1cm} (12)

Figure 5. Reservoir operation flowchart.

- \( H_{rf}(S_{2t}) \) is the average reservoir elevation expressed as a function of the average reservoir storage. It can be obtained by regression of reservoir elevation as a dependant variable and reservoir storage as the predictor.

- \( R_{2t} \) = turbine release at time (month) \( t \), (Mm³)

- \( H_{2t} \) = generating head (m)

- \( H_{min.2t} \) = minimum operating reservoir elevation (m)
\[ \varepsilon_2 = \text{efficiency} \]
\[ S_{2,t} = \text{reservoir storage at time (month) } t, (\text{Mm}^3) \]

2.3.3. Model constraints
The objective function is to be maximized subject to the following constraints.

The mass balance between the inflows and the outflows is given as follows

\[ S_{2,t+1} = S_{2,t} + I_{2,t} - R_{2,t} - L_{2,t} - G_{2,t} \]  \hspace{1cm} (13)

where:
\[ S_{2,t+1} = \text{final storage (initial storage of the next season) for period } t+1, (\text{Mm}^3) \]
\[ S_{2,t} = \text{initial storage for period } t, (\text{Mm}^3) \]
\[ I_{2,t} = \text{reservoir inflow for period } t, (\text{Mm}^3) \]
\[ R_{2,t} = \text{turbine release for period } t, (\text{Mm}^3) \]
\[ L_{2,t} = \text{evaporation losses for period } t, (\text{Mm}^3) \]
\[ G_{2,t} = \text{excess release for period } t, (\text{Mm}^3) \]

The next constraint is for the reservoir capacity at any period \( t \)

\[ S_{2,t, \text{min}} \leq S_{2,t} \leq S_{2,t, \text{max}} \]  \hspace{1cm} (14)

where:
\[ S_{2,t, \text{min}} = \text{Minimum reservoir capacity at any time } t, (\text{Mm}^3) \]
\[ S_{2,t, \text{max}} = \text{Maximum reservoir capacity at any time } t, (\text{Mm}^3) \]
\[ S_{2,t} = \text{the storage at any time } t, (\text{Mm}^3) \]

The constraint on the turbine releases is

\[ R_{2,t, \text{min}} \leq R_{2,t} \leq R_{2,t, \text{max}} \]  \hspace{1cm} (15)

where
\[ R_{2,t, \text{min}} = \text{Minimum turbine release at any time } t, (\text{Mm}^3) \]
\[ R_{2,t, \text{max}} = \text{Maximum turbine release at any time } t, (\text{Mm}^3) \]
\[ R_{2,t} = \text{The turbine release at any time } t, (\text{Mm}^3) \]

Equations (14) and (15) indicate the lower and upper bounds on reservoir storage volume and releases, respectively.

The constraint on hydropower generation (MWH)

\[ Z_{\text{min}} \leq Z_{t} \leq Z_{\text{max}} \]  \hspace{1cm} (16)

where:
\[ Z_{\text{min}} = \text{Minimum hydropower generation at time } t, (\text{MWH}) \]
\[ Z_{\text{max}} = \text{Maximum hydropower generation (Installed capacity) (MWH)} \]
\[ Z_{t} = \text{Hydropower generation at any time } t, (\text{MWH}) \]
Equation (16) provides the lower and upper bounds on hydropower generation.

**Site 5: Available water for downstream users**

The available water for downstream users ($Q_{5,t}$), depends on the Turbine release, excess release (spillage) if there is any, incremental inflow from the watershed areas between the Jebba dam and the gauge site 4 and irrigation water. This is expressed mathematically in Equation 17 as;

$$
\begin{align*}
Q_{4,t} &\leq R_{2,t} + Q_{3-4,t} + G_{2,t} \\
Q_{5,t} &= Q_{4,t} - D_{7,t}
\end{align*}
$$

where:

$Q_{3-4,t} =$ incremental flow from Jebba to site 4 in time $t$, (Mm$^3$)

$G_{2,t} =$ excess release at Jebba (spillage) in time $t$, (Mm$^3$)

$D_{7,t} =$ Diversion water for irrigation at Bacita sugar plantation during period $t$, (Mm$^3$)

**Site 5 and 6: Flood prone area-bacita sugar plantation flood control**

The flood control constraint is for the protection of downstream areas from flood and depends on turbine release, lateral inflow, irrigation water and excess water from spill.

$$
Q_{5,t} \leq q_6
$$

where:

$q_6 =$ the limit on flow at Belle–Bacita gauge site for controlling flooding of sugar cane plantation at Bacita (flood discharge of certain return period, say $T_r = 200$ yrs)

$Q_{5,t} =$ available water for downstream users (Mm$^3$)

**3. Data collection and analysis**

Hydropower data such as the average of reservoir inflow ($I$), storage ($S$), elevation ($H$), turbine release ($Q$), energy generation ($E$), and tail race water level ($T$) for period of 27 years (1984 – 2011) at the Jebba Hydropower station were obtained. The data collected were subjected to statistical analysis to obtain statistical parameters such as mean, median, standard deviation, skewness, coefficient of variance, maximum and minimum values as shown in Tables 2–7. Tables 2–7 show average monthly statistical summaries for reservoir inflow, storage, elevation, turbine release, energy generated and tailrace water level, respectively.

**3.1. Model solution for categories of reservoir inflows**

3.1.1. Operation performance of the hydropower reservoir system under reservoir inflow 95, 90, 75 and 50% Reliability

In solving the formulated model for the hydropower reservoir system and to estimate other associated parameters, MATLAB software for Genetic algorithm was used. For comparison and also to serve as a check, another optimization software (LINGO) was utilized. Its outputs were compared to that of Genetic Algorithm which shows that the outputs are satisfactory. LINGO has the ability to solve nonlinear models, and the availability of the set or vector notation for compactly representing...
large models (Lindo Systems, 2003). The optimal solution obtained at operation performance of 50% reservoir inflow reliability has the total annual energy generation of 42,105.63MWH. The optimal solutions obtained in both Genetic Algorithm and LINGO is presented in Tables 8 – 15. Figures 6–14 show the comparison of optimal outputs generated from Genetic Algorithm and LINGO for the various variables obtained for the 50% inflow reliability. The Genetic Algorithm for the total annual energy generation at operation performance of 95, 90 and 75% reservoir inflow reliability are 21,737.61MWH, 25,650.76 MWH and 30,926.75, respectively.

In Tables 8–15, the meanings of symbols for the variables used are as follows:

- $x_1 = R_{2,i}$ = turbine release at time (month) $t$, (Mm$^3$)
- $x_2 = S_{2,i}$ = initial storage for period $t$, (Mm$^3$)
- $x_3 = S_{2,i+1}$ = final storage (initial storage of the next season) for period $t + 1$, (Mm$^3$)
- $x_4 = I_{2,i}$ = reservoir inflow for period $t$, (Mm$^3$)
- $x_5 = L_{2,i}$ = evaporation losses for period $t$, (Mm$^3$)
- $x_6 = G_{2,i}$ = excess release at Jebba (spillage) in time $t$, (Mm$^3$)
- $x_7 = Q_{3-4,i}$ = incremental flow from Jebba to site 4 in time $t$, (Mm$^3$)
- $x_8 = Q_{4,i} = Q_{5,i}$ = available water for downstream users (Mm$^3$)
- $x_9 = D_{7,i}$ = Diversion water for irrigation at Bacita sugar plantation during period $t$, (Mm$^3$)
- $Z =$ Total energy generated at Jebba

4. Discussion of results
The objective function is to maximize the annual energy for the Jebba hydropower plant which also is the fitness function. The equation for the fitness function is shown in Equation (12) where the average reservoir elevation is expressed as a function of the average storage which is obtained by regression of reservoir elevation as a dependant variable and reservoir storage as the predictor. The model constraints were clearly stated and explained in Equations (13)–(18). This is the general optimization model formulation with the average monthly model fully established and solved. The reservoir inflow is fitted into normal distribution based on the monthly mean and standard deviation of the historical data. The predicted reservoir inflow of 50, 75, 90, and 95% probabilities of exceedence and statistical parameters are presented in Table 16.

The high spread of inflow, storage, energy generation and turbine release and the hydrological process data are scattered and non-uniform throughout the years. However, it is clear that four parameters (inflow, storage, energy generation and turbine release) are closely related. 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. The model fitting charts for all the parameters 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, the values are in ascending order of 50, 75, 90 and 95% which also corresponded to the outputs obtained with Genetic Algorithm and LINGO for all parameters.

The average optimal energy generation obtained is 19% of the observed energy generation but with adequate water supply for downstream users and for irrigation at Bacita sugar plantation throughout the year. The annual optimal evaporation losses is averaged at 58.16 Mm$^3$. In the comparison charts for Genetic Algorithm and LINGO, the trend lines on all charts appeared slightly parallel to one another but with larger outputs for LINGO than that of Genetic Algorithm on turbine release, initial reservoir storage excess release, water available for downstream users and the energy generation. However, the optimal inflow, evaporation losses and the incremental inflow from Jebba to site 4 (Yelwa gauge site) yielded the same outputs on both Genetic Algorithm and LINGO.
### Table 2. Monthly statistical summaries for reservoir inflow data (1984 - 2011)

| Statistical parameter | Jan    | Feb    | Mar    | Apr    | May    | June   | July   | Aug    | Sept   | Oct    | Nov    | Dec    |
|-----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| MEAN                  | 2,816.34 | 2,494.06 | 2,534.55 | 2,476.57 | 2,348.31 | 2,167.84 | 2,074.62 | 4,233.31 | 4,404.78 | 2,699.38 | 2,908.65 |
| MEDIAN                | 2,800.27 | 2,526.86 | 2,622.15 | 2,400.19 | 2,261.91 | 2,094.34 | 1,949.88 | 3,772.66 | 3,747.08 | 2,564.79 | 2,888.66 |
| S.D                   | 999.71  | 819.14  | 857.25  | 752.28  | 748.76  | 615.30  | 787.14  | 1,223.48 | 1,950.59 | 2,548.70 | 877.80  | 693.42  |
| CV                    | 0.35    | 0.33    | 0.34    | 0.30    | 0.32    | 0.28    | 0.38    | 0.44    | 0.46    | 0.58    | 0.33    | 0.24    |
| MIN                   | 0.00    | 962.85  | 1,116.90 | 1,130.12 | 1,146.36 | 1,013.48 | 1,012.44 | 1,076.72 | 1,944.00 | 1,783.82 | 1,337.48 | 1,633.83 |
| MAX                   | 4,218.48 | 3,690.23 | 4,014.92 | 4,059.07 | 3,923.86 | 3,452.54 | 4,464.90 | 6,371.92 | 9,510.05 | 9,728.67 | 4,375.30 | 4,191.70 |
| SKEW                  | -0.66   | -0.21   | 0.00    | 0.11    | 0.30    | 0.18    | 1.27    | 0.85    | 1.26    | 1.04    | 0.28    | -0.08   |

Notes: S.D = Standard Deviation, C.V = Coefficient of variance, MIN = Minimum, MAX = Maximum.
Table 3. Monthly statistical summaries for reservoir storage data (1984–2011)

| Statistical parameter | Jan     | Feb     | Mar     | Apr     | May     | June    | July    | Aug     | Sept    | Oct     | Nov     | Dec     |
|-----------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| MEAN                  | 3,486.86| 3,537.71| 3,523.36| 3,482.14| 3,467.43| 3,463.46| 3,385.64| 3,437.00| 3,633.43| 3,689.46| 3,551.11| 3,521.56|
| MEDIAN                | 3,526.50| 3,566.50| 3,547.50| 3,522.00| 3,531.50| 3,547.50| 3,404.00| 3,462.50| 3,637.00| 3,701.00| 3,551.00| 3,565.00|
| S.D                   | 222.48  | 235.05  | 215.55  | 243.47  | 264.14  | 288.11  | 267.80  | 232.49  | 168.29  | 163.25  | 258.02  | 229.51  |
| CV                    | 0.06    | 0.07    | 0.06    | 0.07    | 0.08    | 0.08    | 0.08    | 0.08    | 0.07    | 0.05    | 0.04    | 0.07    |
| MIN                   | 3,083.00| 3,077.00| 3,106.00| 3,065.00| 3,053.00| 2,925.00| 2,850.00| 2,905.00| 3,146.00| 3,256.00| 3,085.00| 3,031.00|
| MAX                   | 3,854.00| 3,884.00| 3,874.00| 3,850.00| 3,893.00| 3,893.00| 3,786.00| 3,871.00| 3,941.00| 3,911.00| 3,895.00| 3,826.00|
| SKEW                  | −0.13   | −0.57   | −0.30   | −0.20   | −0.20   | −0.63   | −0.45   | −0.48   | −0.69   | −0.70   | −0.45   | −0.72   |

Notes: S.D = Standard Deviation, CV = Coefficient of variance, MIN = Minimum, MAX = Maximum.
### Table 4. Monthly statistical summaries for reservoir elevation data (1984–2011)

| Statistical parameter | Jan    | Feb    | Mar    | Apr    | May    | June   | July   | Aug    | Sept   | Oct    | Nov    | Dec    |
|-----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| MEAN                  | 101.81 | 101.74 | 101.77 | 101.65 | 101.54 | 101.41 | 101.11 | 101.42 | 102.13 | 102.35 | 101.82 | 101.72 |
| MEDIAN                | 101.90 | 101.92 | 101.81 | 101.76 | 101.91 | 101.76 | 101.26 | 101.58 | 102.16 | 102.48 | 101.88 | 101.87 |
| S.D                   | 0.75   | 0.83   | 0.75   | 0.80   | 0.92   | 1.05   | 0.92   | 0.82   | 0.57   | 0.55   | 0.92   | 0.80   |
| C.V                   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   |
| MIN                   | 100.25 | 100.11 | 100.23 | 100.17 | 100.01 | 99.50  | 99.20  | 99.40  | 100.38 | 100.82 | 100.15 | 99.92  |
| MAX                   | 102.87 | 102.87 | 102.98 | 102.98 | 102.91 | 102.65 | 102.74 | 103.07 | 103.06 | 103.00 | 102.78 |        |
| SKEW                  | -0.49  | -0.72  | -0.38  | -0.14  | -0.45  | -0.58  | -0.55  | -0.81  | -0.96  | -0.87  | -0.57  | -0.55  |

Notes: S.D = Standard Deviation, C.V = Coefficient of variance, MIN = Minimum, MAX = Maximum.
Table 5. Monthly statistical summaries for turbine release data (1984–2011)

| Statistical Parameter | Jan  | Feb  | Mar  | Apr  | May  | June | July | Aug  | Sept | Oct  | Nov  | Dec  |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| MEAN                  | 2,923.58 | 2,604.83 | 2,527.23 | 2,529.42 | 2,338.30 | 2,212.31 | 2,083.62 | 2,772.19 | 3,199.80 | 3,558.63 | 2,673.61 | 2,737.17 |
| MEDIAN                | 2,884.77 | 2,753.89 | 2,541.80 | 2,599.83 | 2,130.67 | 2,218.99 | 2,050.96 | 2,847.14 | 3,195.71 | 3,435.64 | 2,435.77 | 2,603.27 |
| S.D                   | 897.38 | 868.41 | 836.34 | 778.08 | 785.68 | 669.85 | 714.46 | 1,045.55 | 1,552.46 | 1,484.54 | 996.33 | 737.81 |
| CV                    | 0.31 | 0.33 | 0.33 | 0.31 | 0.34 | 0.30 | 0.34 | 0.38 | 0.49 | 0.42 | 0.37 | 0.27 |
| MIN                   | 981.50 | 963.50 | 1,007.20 | 1,138.00 | 937.10 | 878.10 | 986.38 | 971.65 | 0.00 | 1,833.10 | 539.14 | 1,376.30 |
| MAX                   | 4,225.90 | 3,974.83 | 3,926.53 | 4,333.82 | 4,017.60 | 3,473.28 | 4,166.74 | 5,094.67 | 7,978.18 | 8,680.70 | 4,427.14 | 4,301.51 |
| SKEW                  | −0.30 | −0.28 | −0.04 | 0.34 | 0.38 | −0.11 | 1.08 | 0.13 | 0.58 | 1.52 | 0.05 | 0.22 |

Notes: S.D = Standard Deviation, CV = Coefficient of variance, MIN = Minimum, MAX = Maximum.
| Statistical parameter | Jan  | Feb  | Mar  | Apr  | May  | June | July | Aug  | Sept | Oct  | Nov  | Dec  |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| MEAN                  | 201,149.2 | 179,092.5 | 183,426.2 | 174,818.9 | 167,722.0 | 155,854.9 | 150,044.0 | 179,755.6 | 223,874.2 | 235,006.1 | 191,259.0 | 189,999.9 |
| MEDIAN                | 200,568.5 | 178,717.5 | 190,517.5 | 179,794.0 | 149,026.5 | 146,192.0 | 137,592.5 | 173,563.5 | 218,084.0 | 249,006.0 | 189,216.5 | 174,543.0 |
| S.D                   | 66,932.4 | 60,131.5 | 55,615.5 | 58,491.6 | 57,464.3 | 60,268.7 | 57,812.2 | 71,105.8 | 66,234.4 | 73,236.9 | 63,839.4 | 56,410.2 |
| CV                    | 0.3    | 0.3   | 0.3   | 0.3   | 0.3   | 0.4   | 0.4   | 0.4   | 0.3   | 0.3   | 0.3   | 0.3   |
| MIN                   | 63,001.0 | 68,534.0 | 79,424.0 | 78,188.0 | 78,259.0 | 61,534.0 | 59,956.0 | 66,334.0 | 114,315.0 | 72,912.0 | 93,644.0 | 93,711.0 |
| MAX                   | 331,090.4 | 287,401.0 | 281,633.8 | 288,139.7 | 286,856.6 | 271,382.4 | 281,232.0 | 305,337.6 | 360,842.0 | 357,140.0 | 303,264.0 | 306,904.5 |
| SKEW                  | -0.0030 | -0.0416 | -0.2221 | 0.1751 | 0.3571 | 0.4943 | 0.9587 | 0.3055 | 0.2118 | -0.3119 | 0.2943 | 0.3068 |

Notes: S.D = Standard Deviation, CV = Coefficient of variance, MIN = Minimum, MAX = Maximum.
Table 7. Monthly statistical summaries for tail race water level data (1984–2011)

| Statistical parameter | Jan   | Feb   | Mar   | Apr   | May   | June  | July  | Aug   | Sept  | Oct   | Nov   | Dec   |
|-----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| MEAN                  | 73.92 | 73.77 | 73.67 | 73.58 | 73.43 | 73.33 | 73.22 | 73.63 | 74.37 | 74.58 | 73.84 | 73.79 |
| MEDIAN                | 74.00 | 73.82 | 73.65 | 73.54 | 73.30 | 73.34 | 73.26 | 73.61 | 74.23 | 74.42 | 73.82 | 73.73 |
| S.D                   | 0.47  | 0.52  | 0.47  | 0.44  | 0.43  | 0.42  | 0.46  | 0.63  | 0.89  | 1.10  | 0.57  | 0.48  |
| C.V                   | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  |
| MIN                   | 72.91 | 72.79 | 72.89 | 72.90 | 72.66 | 72.57 | 72.28 | 72.45 | 73.05 | 73.15 | 72.77 | 73.07 |
| MAX                   | 74.88 | 75.01 | 74.65 | 74.59 | 74.39 | 74.10 | 74.39 | 74.65 | 76.70 | 76.85 | 74.83 | 74.70 |
| SKEW                  | -0.1987 | -0.0180 | 0.1464 | 0.3619 | 0.5166 | -0.0309 | 0.3872 | -0.1878 | 0.8568 | 0.8704 | 0.0387 | 0.2081 |

Notes: S.D = Standard Deviation, C.V = Coefficient of variance, MIN = Minimum, MAX = Maximum.
Table 8. Genetic algorithm output of reservoir operation performance under reservoir inflow of 50% reliability

| Month | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $Z$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
| $i$   | $R_{x1}$ | $S_{x1}$ | $S_{x1-1}$ | $I_{x1}$ | $L_{x1}$ | $G_{x1}$ | $Q_{x1}$ | $Q_{x1-x1}$ | $Q_{x1}$ | $D_{x1}$ |     |
| 1     | 1,762.68 | 2,880.001 | 3,880 | 2,816.34 | 53.66 | 0 | 1,789.58 | 26.9 | 1,739.58 | 50 | 5,143.485 |
| 2     | 1,420.13 | 2,880.001 | 3,880 | 2,494.06 | 73.93 | 0 | 1,442.26 | 22.13 | 1,392.26 | 50 | 4,143.927 |
| 3     | 1,461.52 | 2,880.001 | 3,880 | 2,534.55 | 73.03 | 0 | 1,483.23 | 21.71 | 1,433.23 | 50 | 4,264.703 |
| 4     | 1,394.88 | 2,880.001 | 3,880 | 2,476.57 | 81.69 | 0 | 1,416.07 | 21.19 | 1,366.07 | 50 | 4,070.248 |
| 5     | 1,284.89 | 2,880.001 | 3,880 | 2,348.31 | 63.42 | 0 | 1,305.39 | 20.5 | 1,255.39 | 50 | 3,749.3 |
| 6     | 1,114.51 | 2,880.001 | 3,880 | 2,167.84 | 53.33037 | 0 | 1,134.47 | 19.9601 | 1,084.47 | 50 | 3,252.13 |
| 7     | 1,031.29 | 2,880.001 | 3,880 | 2,074.62 | 43.33 | 0 | 1,050.46 | 19.17 | 1,000.46 | 50 | 3,009.297 |
| 8     | 1,238.77 | 2,880.002 | 3,880 | 2,784.15 | 37.391 | 0 | 1,773.852 | 27.092 | 1,723.856 | 49.996 | 3,614.71 |
| 9     | 2,085.225 | 3,224.844 | 3,880 | 4,233.31 | 42.181 | 1,450.747 | 3,582.001 | 46.03 | 3,532 | 50 | 763.5143 |
| 10    | 2,030.548 | 3,067.054 | 3,880 | 4,404.78 | 58.601 | 1,502.684 | 3,582.001 | 48.77 | 3,532 | 50 | 3,114.455 |
| 11    | 1,159.929 | 2,880.069 | 3,879.96 | 2,699.381 | 60.75099 | 478.8097 | 1,663.85 | 25.0949 | 1,614.347 | 49.60178 | 3,384.079 |
| 12    | 1,232.477 | 2,880.064 | 3,879.943 | 2,908.651 | 56.57098 | 619.7242 | 1,881.059 | 28.8438 | 1,831.433 | 49.64024 | 3,595.78 |

42,105.63
| Month | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $Z$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
| 1     | 1,082.88 | 2,880.001 | 3,880 | 2,136.54 | 53.66 | 0 | 1,109.78 | 26.9 | 1,059.78 | 50 | 3,159.836 |
| 2     | 863.1103 | 2,880.001 | 3,880 | 1,937.04 | 73.93 | 0 | 885.2403 | 22.13 | 835.2403 | 50 | 2,518.548 |
| 3     | 878.5902 | 2,880.001 | 3,880 | 1,951.62 | 73.03 | 0 | 900.7202 | 22.13 | 850.7202 | 50 | 2,563.718 |
| 4     | 883.33 | 2,880.001 | 3,880 | 1,965.02 | 81.69 | 0 | 904.52 | 21.19 | 854.52 | 50 | 2,577.551 |
| 5     | 800.0001 | 2,880.001 | 3,855.73 | 1,839.15 | 63.42 | 0 | 820.5003 | 20.50014 | 3,532 | 48.99979 | 2,334.392 |
| 6     | 800 | 2,880.001 | 3,776.11 | 1,749.44 | 53.33 | 0 | 819.9603 | 19.96034 | 769.9603 | 50 | 2,334.394 |
| 7     | 800 | 2,880.001 | 3,576.03 | 1,539.36 | 43.33 | 0 | 819.17 | 19.17 | 769.17 | 50 | 2,334.394 |
| 8     | 810.1329 | 2,880.002 | 3,880 | 1,952.18 | 37.39073 | 104.6579 | 941.8811 | 27.09076 | 892.0026 | 49.99855 | 2,363.957 |
| 9     | 1,020.355 | 2,880.218 | 3,879.988 | 2,906.9 | 42.18099 | 844.5938 | 1,911.02 | 46.07228 | 1,861.499 | 49.93473 | 2,975.746 |
| 10    | 816.9695 | 2,886.801 | 3,873.208 | 2,671.67 | 58.60099 | 809.6927 | 1,689.04 | 62.35778 | 1,679.842 | 9.202419 | 2,342.799 |
| 11    | 861.4433 | 2,880.079 | 3,879.999 | 2,102.48 | 60.751 | 180.3649 | 1,066.928 | 25.10168 | 1,017.82 | 49.62831 | 2,513.189 |
| 12    | 996.6549 | 2,880.002 | 3,880 | 2,437.13 | 56.57098 | 383.9055 | 1,409.29 | 28.73061 | 1,359.344 | 49.99609 | 2,908.223 |
Table 10. Genetic algorithm output of reservoir operation performance under reservoir inflow of 90% reliability

| Month | $x_i$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $z$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
| $i$   | $R_{2i}$ | $S_{2i}$ | $S_{2i+1}$ | $I_{2i}$ | $L_{2i}$ | $G_{2i}$ | $Q_{2i}$ | $Q_{2i-4j}$ | $Q_{3i}$ | $D_{2i}$ |
| 1     | 800.0002 | 2,880.001 | 3,553.05 | 1,526.71 | 53.66 | 0    | 826.9002 | 26.9   | 776.901 | 50    | 2,334.392 |
| 2     | 800    | 2,880.001 | 3,443.44 | 1,437.37 | 73.93 | 0    | 822.1301 | 22.1305 | 772.1301 | 50    | 2,334.394 |
| 3     | 800    | 2,880.001 | 3,435.67 | 1,428.7  | 73.03 | 0    | 821.71  | 21.71002 | 771.71  | 50    | 2,334.394 |
| 4     | 800    | 2,880.001 | 3,504.44 | 1,506.13 | 81.69 | 0    | 821.19  | 21.19   | 771.19  | 50    | 2,334.394 |
| 5     | 800    | 2,880.001 | 3,398.99 | 1,382.41 | 63.42 | 0    | 820.5001 | 20.5009 | 770.5001 | 50    | 2,334.393 |
| 6     | 800    | 2,880.001 | 3,400.77 | 1,374.1  | 53.33 | 0    | 819.96  | 19.96   | 769.96  | 50    | 2,334.394 |
| 7     | 800    | 2,880.001 | 3,095.88 | 1,059.21 | 43.33 | 0    | 819.17  | 19.17   | 769.17  | 50    | 2,334.393 |
| 8     | 807.9877 | 2,888.503 | 3,145.474 | 1,205.86 | 37.39099 | 103.5103 | 955.0718 | 43.53449 | 955.0184 | 0.065041 | 2,306.866 |
| 9     | 800.0002 | 2,880.002 | 3,130.81 | 1,717.04 | 42.1805 | 624.0507 | 1,470.083 | 46.03033 | 1,420.122 | 49.99887 | 2,334.388 |
| 10    | 800.0008 | 3,614.371 | 2,880.001 | 1,116.961 | 58.60085 | 792.7301 | 1,641.516 | 48.77035 | 1,591.515 | 49.99978 | 0 |
| 11    | 800.0002 | 2,880.002 | 3,467.42 | 1,567.02 | 60.7505 | 118.8507 | 94.38332 | 24.98033 | 893.8722 | 49.99887 | 2,334.388 |
| 12    | 800.0015 | 2,880.006 | 3,850.322 | 2,014.14 | 56.571 | 187.2506 | 1,015.998 | 28.73152 | 966.1211 | 49.99684 | 2,334.368 |
Table 11. Genetic algorithm output of reservoir operation performance under reservoir inflow of 95% reliability

| Month | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $Z$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
| i     |       |       |       |       |       |       |       |       |       |       |     |
| 1     | 800   | 2,880.001 | 3,198.16 | 1,171.82 | 53.66 | 0 | 826.9 | 26.90004 | 776.9 | 50 | 2,334.394 |
| 2     | 800.0002 | 2,880.001 | 3,152.64 | 1,146.57 | 73.93 | 0 | 822.1302 | 22.13 | 772.131 | 50 | 2,334.392 |
| 3     | 800   | 2,880.001 | 3,131.35 | 1,124.38 | 73.03 | 0 | 821.71 | 21.71 | 771.71 | 50 | 2,334.394 |
| 4     | 800   | 2,880.001 | 3,237.38 | 1,239.07 | 81.69 | 0 | 821.19 | 21.19 | 771.19 | 50 | 2,334.394 |
| 5     | 800   | 2,880.001 | 3,133.18 | 1,116.6 | 63.42 | 0 | 820.5001 | 20.50007 | 770.5001 | 50 | 2,334.394 |
| 6     | 800   | 2,880.001 | 3,182.34 | 1,155.67 | 53.33 | 0 | 819.96 | 19.96 | 769.96 | 50 | 2,334.394 |
| 7     | 800   | 2,943.56 | 2,880 | 779.7702 | 43.33033 | 0 | 819.17 | 19.17 | 769.17 | 50 | 1,958.123 |
| 8     | 800   | 3,040.391 | 2,880 | 771.5203 | 37.39036 | 94.52058 | 921.6117 | 27.0904 | 871.6139 | 49.99953 | 1,384.883 |
| 9     | 800.0016 | 3,321.667 | 2,880.015 | 1,024.581 | 42.18052 | 624.0502 | 1,470.082 | 46.03028 | 1,420.09 | 49.99898 | 0 |
| 10    |       |       |       |       |       |       |       |       |       |       |     |
| 11    | 800.0002 | 2,880.002 | 3,155.81 | 1,255.41 | 60.7505 | 118.8507 | 943.8332 | 24.98033 | 893.8722 | 49.99887 | 2,334.388 |
| 12    | 800.0274 | 2,880.061 | 3,604.17 | 1,767.98 | 56.57099 | 187.2718 | 1016.163 | 28.76512 | 966.3859 | 49.93833 | 2,334.119 |
### Table 12. LINGO output of reservoir operation performance under reservoir inflow of 50% reliability

| Month | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $Z$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
| 1     | 3,350 | 3,880 | 2,880 | 2,816 | 53.66 | 0     | 3,576.9| 26.9  | 3,532 | 44.9  | 15,911.1 |
| 2     | 3,420.13 | 3,880 | 2,880 | 2,490.06 | 73.93 | 0     | 3,442.26| 22.13 | 3,421.36 | 20.94 | 15,329.02 |
| 3     | 3,461.52 | 3,880 | 2,880 | 2,534.55 | 73.03 | 0     | 3,483.23| 21.71 | 3,457.9 | 25.33 | 15,514.53 |
| 4     | 3,394.88 | 3,880 | 2,880 | 2,476.57 | 81.69 | 0     | 3,416.07| 21.19 | 3,398.54 | 17.53 | 15,215.85 |
| 5     | 3,284.89 | 3,880 | 2,880 | 2,348.31 | 63.42 | 0     | 3,305.39| 20.5  | 3,296.71 | 8.68  | 14,722.88 |
| 6     | 3,114.51 | 3,880 | 2,880 | 2,167.84 | 53.33 | 0     | 3,134.47| 19.96 | 3,134.47 | 0     | 13,959.23 |
| 7     | 3,031.29 | 3,880 | 2,880 | 2,074.62 | 43.33 | 0     | 3,050.46| 19.17 | 3,050.46 | 0     | 13,586.24 |
| 8     | 3,460.39 | 3,880 | 2,880 | 2,784.15 | 37.39 | 94.52 | 3,582   | 27.09 | 3,532 | 50    | 15,509.47 |
| 9     | 1,305.04 | 3,224.84 | 3,880 | 4,233.31 | 42.18 | 2,230.91 | 3,582 | 46.03 | 3,532 | 50    | 0 |
| 10    | 842.02 | 3,067.05 | 3,880 | 4,404.78 | 58.6  | 2,691.21 | 3,582 | 48.77 | 3,532 | 50    | 0 |
| 11    | 3,438.17 | 3,880 | 2,961.61 | 2,699.38 | 60.75 | 118.85 | 3,582 | 24.98 | 3,532 | 50    | 15,409.88 |
| 12    | 3,366.02 | 3,880 | 3,178.81 | 2,908.65 | 56.57 | 187.25 | 3,582 | 28.73 | 3,532 | 50    | 15,086.5 |

Total: 150,244.7
Table 13. LINGO output of reservoir operation performance under reservoir inflow of 75% reliability

| Month | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $Z$  |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|
| 1     | 3,082.88 | 3,880 | 2,880 | 2,136.54 | 53.66 | 0     | 3,109.78 | 26.9  | 3,090.78 | 19.55 | 13,817.47 |
| 2     | 2,863.1 | 3,880 | 2,880 | 1,937.04 | 73.94 | 0     | 2,885.23 | 22.13 | 2,864.33 | 20.9  | 12,832.41 |
| 3     | 2,878.59 | 3,880 | 2,880 | 1,951.62 | 73.03 | 0     | 2,900.72 | 22.13 | 2,875.39 | 25.33 | 12,901.84 |
| 4     | 2,833.33 | 3,880 | 2,880 | 1,965.02 | 81.69 | 0     | 2,904.52 | 21.19 | 2,886.99 | 17.53 | 12,923.09 |
| 5     | 2,775.73 | 3,880 | 2,880 | 1,839.15 | 63.42 | 0     | 2,796.23 | 20.5  | 2,787.55 | 8.68  | 12,440.82 |
| 6     | 2,696.11 | 3,880 | 2,880 | 1,749.44 | 53.33 | 0     | 2,716.07 | 19.96 | 2,716.07 | 0     | 12,083.97 |
| 7     | 2,496.03 | 3,880 | 2,880 | 1,539.36 | 43.33 | 0     | 2,515.2  | 19.17 | 2,515.2  | 0     | 11,187.21 |
| 8     | 2,820.27 | 3,880 | 2,880 | 1,952.18 | 37.39 | 0     | 2,941.88 | 27.09 | 2,941.88 | 50    | 12,640.45 |
| 9     | 2,911.92 | 3,880 | 3,208.75 | 2,906.9 | 42.18 | 624.05 | 3,582  | 46.03 | 3,532  | 50    | 13,051.23 |
| 10    | 2,740.5 | 3,880 | 2,959.84 | 2,671.67 | 58.6 | 792.73 | 3,582  | 48.77 | 3,532  | 50    | 12,282.92 |
| 11    | 2,922.88 | 3,880 | 2,880 | 2,102.48 | 60.75 | 118.85 | 3,066.71 | 24.98 | 3,051.4 | 15.31 | 13,100.35 |
| 12    | 3,193.31 | 3,880 | 2,880 | 2,437.13 | 56.57 | 187.25 | 3,409.29 | 28.73 | 3,392.38 | 16.91 | 14,312.42 |
| Month | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $Z$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|-----|
| $i$   | $R_{ij}$ | $S_{2i}$ | $S_{2i+1}$ | $I_{2i}$ | $L_{2j}$ | $G_{2i}$ | $Q_{3i}$ | $Q_{4j}$ | $Q_{5j}$ | $D_{ij}$ |     |
| 1     | 3.550  | 3.880  | 2.880  | 1.526.71 | 53.66  | 0     | 3.576.9 | 26.9   | 3.532  | 44.9   | 15.911.1 |
| 2     | 2.363.44 | 3.880 | 2.880  | 1.437.37 | 73.94  | 0     | 2.385.57 | 22.13  | 2.364.67 | 20.9    | 10.592.94 |
| 3     | 2.355.67 | 3.880 | 2.880  | 1.428.7  | 73.03  | 0     | 2.377.38 | 21.71  | 2.352.05 | 25.33   | 10.558.11 |
| 4     | 2.424.44 | 3.880 | 2.880  | 1.506.13 | 81.69  | 0     | 2.445.63 | 21.19  | 2.428.1 | 17.53   | 10.866.34 |
| 5     | 2.318.99 | 3.880 | 2.880  | 1.382.41 | 63.42  | 0     | 2.339.49 | 20.5   | 2.330.81 | 8.68    | 10.393.71 |
| 6     | 2.320.77 | 3.880 | 2.880  | 1.374.1  | 53.33  | 0     | 2.340.73 | 19.96  | 2.340.73 | 0       | 10.401.69 |
| 7     | 2.015.88 | 3.880 | 2.880  | 1.059.21 | 43.33  | 0     | 2.035.05 | 19.17  | 2.035.05 | 0       | 9.035.174 |
| 8     | 2.073.95 | 3.880 | 2.880  | 1.205.86 | 37.39  | 94.52 | 2.195.56 | 27.09  | 2.195.56 | 0       | 9.295.44 |
| 9     | No feasible solution |          |        |        |        |       |        |        |        |        |     |
| 10    | 1,265.63 | 3.880 | 2.880  | 1,116.96 | 58.6   | 792.73 | 2,107.13 | 48.77  | 2,097.93 | 9.2    | 5,672.554 |
| 11    | No feasible solution |          |        |        |        |       |        |        |        |        |     |
| 12    | No feasible solution |          |        |        |        |       |        |        |        |        |     |
Table 15. LINGO output of reservoir operation performance under reservoir inflow of 95% reliability

| Month | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $Z$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|-----|
| i     | $R_{ji}$ | $S_{ji}$ | $S_{ji+1}$ | $I_{ji}$ | $L_{ji}$ | $G_{ji}$ | $Q_{ji}$ | $Q_{ji+1}$ | $Q_{ji}$ | $D_{ji}$ |     |
| 1     | 3,350  | 3,880  | 2,880  | 1,171.82 | 53.66 | 0       | 3,576.9  | 26.9   | 3,532  | 44.9    | 15,911.1|
| 2     | 2,072.63 | 3,880  | 2,880  | 1,146.37 | 73.94 | 0       | 2,094.76 | 22.13  | 2,073.86 | 20.9    | 9,289.528|
| 3     | 2,051.35 | 3,880  | 2,880  | 1,124.38 | 73.03 | 0       | 2,073.06 | 21.71  | 2,047.73 | 25.33   | 9,194.151|
| 4     | 2,157.38 | 3,880  | 2,880  | 1,239.07 | 81.69 | 0       | 2,178.58 | 21.19  | 2,161.04 | 17.53   | 9,669.377|
| 5     | 2,053.18 | 3,880  | 2,880  | 1,116.6  | 63.42 | 0       | 2,073.68 | 20.5   | 2,065  | 8.68    | 10,393.71|
| 6     | 2,102.34 | 3,880  | 2,880  | 1,155.67 | 53.33 | 0       | 2,122.3  | 19.96  | 2,122.3 | 0       | 9,422.688|
| 7     | 1,736.44 | 3,880  | 2,880  | 779.77   | 43.33 | 0       | 1,755.61 | 19.17  | 1,755.61 | 0       | 7,782.724|
| 8     | 1,639.61 | 3,880  | 2,880  | 771.52   | 37.39 | 94.52   | 1,761.22 | 27.09  | 1,761.22 | 0       | 7,348.732|
| 9     | 1,358.35 | 3,880  | 2,880  | 1024.58  | 42.18 | 624.05  | 2,028.43 | 46.03  | 2,028.43 | 0       | 6,088.125|
| 10    | No feasible solution | | | | | | | | | | |
| 11    | 2,075.81 | 3,880  | 2,880  | 1,255.41 | 60.75 | 1,18.85 | 2,219.64 | 24.98  | 2,204.33 | 15.31   | 9,303.78|
| 12    | 2,524.16 | 3,880  | 2,880  | 1,767.98 | 56.57 | 187.25  | 2,740.14 | 28.73  | 2,723.23 | 16.91   | 11,313.29|
One unique pattern is the variation of flow pattern within the months of July through to September for both optimization models. This is actually about the time that the hydrological events peak up.
Figure 9. GA and LINGO comparison for optimal reservoir inflow.

Figure 10. GA and LINGO comparison for optimal evaporation losses.

Figure 11. GA and LINGO comparison for optimal excess release.

Figure 12. GA and LINGO comparison for optimal incremental flow From Jebba.
5. Conclusion

The optimal solution obtained at operation performance of 50% reservoir inflow reliability has the total annual energy generation of 42,105.63MWH. The Genetic Algorithm outputs for the total annual energy generation at operation performance of 95, 90 and 75% reservoir inflow reliability are 15,964.48MWH, 21,009.53 MWH and 20,798.58 MWH, respectively. In the probability of exceedence (reliability of flow) computed using normal distribution, the values are in ascending orders in the Table 16. Reservoir inflow of different reliabilities (probability of exceedence) and statistical parameters

| Probability of exceedence (Reliability of flow) | P  | 50%  | 75%  | 90%  | 95%  | Mean | Standard deviation |
|-----------------------------------------------|----|------|------|------|------|------|-------------------|
| Month K | 0  | -0.675 | -1.285 | -1.645 | (Mm³) | (Mm³) |
| Jan     | 2,816.34 | 2,136.54 | 1,526.71 | 1,171.82 | 2,816.34 | 999.71 |
| Feb     | 2,494.06 | 1,937.04 | 1,437.37 | 1,146.57 | 2,494.06 | 819.14 |
| Mar     | 2,534.55 | 1,951.62 | 1,428.70 | 1,124.38 | 2,534.55 | 857.25 |
| Apr     | 2,476.57 | 1,965.02 | 1,506.13 | 1,239.07 | 2,476.57 | 752.28 |
| May     | 2,348.31 | 1,839.15 | 1,382.41 | 1,116.60 | 2,348.31 | 748.76 |
| Jun     | 2,167.84 | 1,749.44 | 1,374.10 | 1,155.67 | 2,167.84 | 615.30 |
| Jul     | 2,074.62 | 1,539.36 | 1,059.21 | 779.77 | 2,074.62 | 787.14 |
| Aug     | 2,784.15 | 1,952.18 | 1,205.86 | 771.52 | 2,784.15 | 1,223.48 |
| Sept    | 4,233.31 | 2,906.90 | 1,717.04 | 1,024.58 | 4,233.31 | 1,950.59 |
| Oct     | 4,404.78 | 2,671.67 | 1,116.96 | 212.17 | 4,404.78 | 2,548.70 |
| Nov     | 2,699.38 | 2,102.48 | 1,567.02 | 1,255.41 | 2,699.38 | 877.80 |
| Dec     | 2,908.65 | 2,437.13 | 2,014.14 | 1,767.98 | 2,908.65 | 693.42 |

Note: Where: P = probability of exceedence and K is the reliability function.
order of 50, 75, 90 and 95% which also corresponded to the outputs obtained with Genetic Algorithm and LINGO for all parameters. The average optimal energy generation obtained is 19% of the observed energy generation but with adequate water supply for downstream users and for irrigation at Bacita sugar plantation throughout the year. The annual optimal evaporation losses is averaged at 58.16 Mm$^3$. It can then be summarized that GA can be applied to develop the optimal operation of a reservoir system. In case of changes in the operating conditions that could arise due to change in hydrological factors, the methodology developed in this study can be used to develop a new rule curve for reservoir operation. The application of Genetic Algorithm will lead to a more realistic and reliable optimal value for the improvement of hydroelectric power generations and flood management, which would guide decision makers in the power sector.

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