AMSE JOURNALS –2014-Series: Modelling C; Vol. 75; N° 1; pp 22-44

Submitted Jan. 2014; Revised June 20, 2014; Accepted July 15, 2014

Sequential Simulation of Integrated Hydropower Releases: Case Study of Ero-Omola Falls, Kwara State, Nigeria.

*B.F. Sule, **A.O. Ogunlela and ***K. M. Lawal

*Director, National Centre for Hydropower Research and Development, University of Ilorin, Ilorin, Nigeria.
**Agricultural and BioSystems Engineering Department, University of Ilorin, Ilorin, Nigeria
***Catchment Director, Nigeria Integrated Water Resources Management Commission, Abuja, Nigeria.
(maroofkular@gmail.com)

Abstract:

The sequent peak algorithm and sequential streamflow routing technique were used to simulate integrated development of Ero-Omola Falls, for hydropower, water supply, irrigation and flood control. The analysis indicated hydropower releases of $21m^3/s$, municipal water supply of $0.538m^3/s$, irrigation water supply of $0.24m^3/s$ and ecological water releases of $1.6 \times 10^{-3}m^3/s$. The result shows that the entire reservoir was drafted effectively for hydropower generation with minimal hydraulic losses of about $1.83m^3/s$. The simulation result indicated about 20.6% more potential hydropower, while additional 23.4% annual energy could be generated. The computed net head routed through the usable discharge falls within the minimum range of head and discharge respectively for a cross-flow turbine recommended for the scheme. The results established that conjunctive use of hydropower releases is an effective mitigation measures against seasonal flooding downstream of power plant in addition to allowing for withdrawal for other uses such as water supply and irrigation.

Keywords: Integrated Hydropower Development, Sequential Routing, Simulation,

1. Introduction

Sequential simulation analysis of streamflow associated with hydropower is of paramount importance in the planning, design and operation of water resources development project. In order to design and construct hydroelectric systems, the analysis of the system (runoff or reservoirs and power plants) operations over a representative hydrologic period is required (Zolgay and Stedinger, 1991). This may be done by using mathematical simulation for analysis of hydropower reservoir systems. Descriptive simulation models due to their computational advantages are able to consider more details of real systems than optimization model (Kelman, 1980). Sequential Stream flow Routing (SSR) is a common method for assessing energy potential in practical hydropower projects design and operation in most part of the world (Labaide, 2004). The quality and accuracy of hydrologic and hydraulic analysis can govern the project feasibility and engineering design to a great extent. The most common hydraulic parameters of interest to engineers are the temporal and spatial distribution of depth and velocity of various discharges. Methods for determining these parameters vary considerably depending on the complexity of the flow pattern, time and budget limitations, data availability, applications of results, available equipment, etc. The general practice has been to use one dimensional steady state algorithms for flurial streams and two dimensional unsteady state models for lakes, reservoirs and coastal projects (Koch-Guibert, 1985). The diversity of hydro project provides engineers with a range of challenging hydrodynamic problems such as flood routing in rivers, flood plain hydraulics, urban storm drainages, circulation in lakes and reservoir that must be dealt with. While all of these are basically three dimensional flow problems, some of them may be approximated adequately either by one–dimensional or two dimensional mathematical models. Numerical flows simulation plays an important role in optimization of the hydraulic turbines and other components of a hydropower plant. The roles include:

a) Prediction of power output of turbine
b) Achievement of maximum hydraulic efficiency
c) avoiding penstock cavitation
d) minimizing plant vibration

Beard and Kumar (1999) re-appraised the efficiency of Sequential Stream flow Routing (SSR) technique with optimization of reservoir inflow to meeting energy demand of Chatawa reservoir in Nepal. They reported that SSR is an acceptable method for assessing energy potential in practical hydropower projects designs and operations. In order to simulate sequential releases an iterative single period linear programming (LP) model was utilized. The linear programming model minimizes the sum of reservoir releases and maximizes the sum of reservoir storages. Reservoir optimization for hydropower, irrigation & municipal water supply was simulated by Hingis et al (2001) where maximization of energy output was considered as the objective function, while reservoir characteristics, the irrigation requirements, water supply and ecological needs were included in the constraints. Beard (1982) utilized Monte Carlo technique to extract maximum degree of pertinent information from monthly stream flow data and generated values whose statistical characteristics were consistent with the observed monthly stream flow data. Nash (1984) deployed hourly rainfall of annual storms to develop a non linear mathematical model to represent the stochastic process of the hourly rainfalls in which the random variables denote trend components of various functions. It was found that the non-stationary Markov chain model is consistently satisfactory and most practical for the purpose. Analysis of low flow series were also reported by Jensens (1998) where the low flows in m^3/s were arranged in decreasing order of magnitude and were ranked accordingly using the Weibul algorithms. It is widely believed that reservoir operations policy alone may not guarantee security against seasonal flooding. The formulation of sustainable conjunctive use of hydropower releases is the best mitigation measures against seasonal flooding of farmland downstream of the dam. Conjunctive use of hydropower releases involves provision of fish passes, water supply facility, irrigation and drainages as well as ecological water balance for downstream eco-systems (IHA, 2007). It has also proved to be the most effective and most sustainable ways of controlling flood since almost 90% of releases would be diverted for useful purposes. The conjunctive use of hydropower releases also ensures that economic activities of benefitting communities are not disconnected by developmental projects (IHA, 2004).

1. Study Approach and Methodology

Accumulation of reliable hydrological data for hydropower development projects demands intelligent and painstaking endeavour and continuous effort. Inadequate water availability has contributed significantly to low capacity utilization and failure of most hydropower plants in Nigeria (Umolu, 2006). Over optimism and conclusions based on insufficient and inaccurate streamflow data are common and are sources of economic waste to government. Over or under estimation of runoff for hydropower projects are frequently reflected in the inability to operate the plants at full capacity soon after completion. The problem is compounded by the occurrence of climatic cycle which cannot as yet be predicted with precision, together with wide variation of precipitation and streamflow from season to season. This study was carried out in three stages. These are (a) development of monthly flow rating equations, (b) extension of streamflow data, and (d) sequent peak analysis and simulation.

The study area is located along Osi- Isolo-Ajuba Road off Osi-Idofin road in Oke-Ero LGA, Kwara State of Nigeria. It is about 116 km from Ilorin the state capital. The height of the fall is about 59.01m high. The catchment area of Ero-Omola-Falls is about 145km^2 with contribution from two rivers namely, Ero-river from Iddo- Faboro near Ifaki in Ekiti State and Odo-Otun river from Ajuba. Ero-Omola Falls lies between Latitude North N08^0 09' 34.6" and N08$^{0\ 09'}$ 30.8" and between Longitude East E 05^0 14' 07.4" and E 05^0 14' 06.7". Figure 1 shows map of Nigeria and the location of the study area.

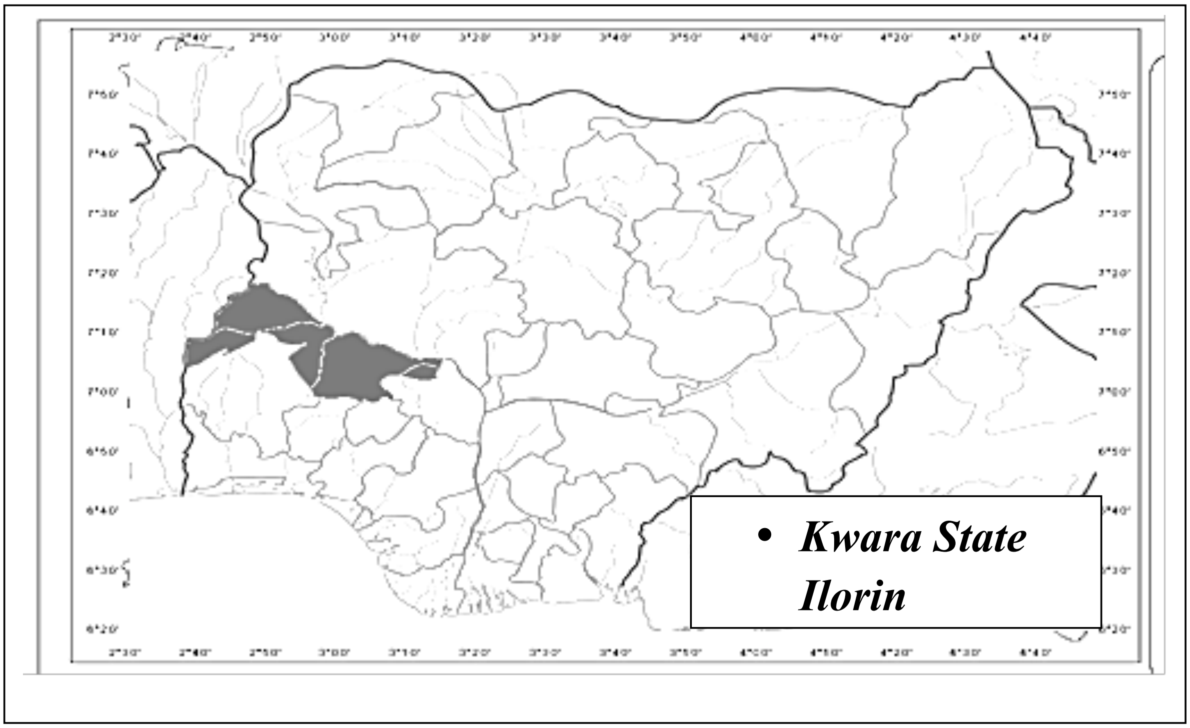


Figure 1: Project Location Map

2.1 Development of Monthly Flow Rating Equations from Streamflow Data

A staff gauge is the simplest device for measuring river stage or water surface elevation. The staff gauge is a graduated self-illuminated strip of metal marked in metres and fractions thereof. Water levels were read daily, recorded and collated on monthly basis at the gauging station at Ero-Omola Falls from 2009 to 2011. Streamflow discharge measurement were taken several time and used along with gauge heights, to develop the rating equations. In general for a gauge height H (m); the discharge Q (m^3/s) is related to height H (m) as (Punmia and Pande (2008) :

$$Q = K\,(H +/\!- H_o)^{n} \tag{1}$$

When $H_o=0$,
The rating equation is given as (Sharma, 1979)

$$Q = KH^n \qquad \textbf{\textit{(2)}}$$

Where

Q = Discharge (m^3/s)

H = Gauge Height (m)

H_o = Gauge Height when the flow is zero (m)

n and k are constants

This is a parabolic equation which plots as a straight line on double logarithmic graph sheet. K & n are determined using the least square methods

2.2 Extension of Streamflow Data

One year stream flow data generated by the rating equation at Ero-Omola Falls, Kwara state, was extended in order to fulfill other hydrological analysis requirement. In order to achieve this, the model proposed by Thomas and Fierring in 1962 (McMachon and Mein, 1978) was adopted. The model utilized Markov theory to represent actual stream flow when the monthly stream flow, qi, are normally distributed and follow a first – order auto regressive model. The algorithm for the Thomas and Fierring model is giving as Karamouz (2003):

$$q_{i+1} = \bar{q}_{j+1} + b_{j,j+1}\left(q_i - \bar{q}_j\right) + Z_{i+1}\ S_{j+1}\left(1 - r_{j,j+1}{}^2\right)^{1/2} \qquad (3)$$

$$X_{i+1} = \mu_{x(i+1)} + b_{x(j,j+1)}\left(X_i - \mu_{x,i}\right) + k_{i+1} s_{x(j+1)}\left(\sqrt{\left(1 - r^2_{x(j,j+1)}\right)}\right) \qquad (4)$$

$$X_{i+1} = \mu_{x(i+1)} + b_{x(j,j+1)}\left(X_i - \mu_{x,i}\right) + k_{i+1} S_{x(j+1)}\left(\sqrt{\left(1 - r^2_{x(j,j+1)}\right)}\right)$$

where $X_i = \ln q_i$; q_j = monthly flow (5)

2.3 Sequent Peak Algorithm

It is imperative to make provision for a reservoir due to three months break of inflow at Ero-Omola during the dry season. This will allow the storage to provide the needed flow to the turbines uninterrupted throughout the year. The capacity required for a reservoir depends upon the inflow available and the demand. If the available inflow in the river is always greater than the demand, there is no storage required. On the other hand, if the inflow in the river is small but the demand is high, a large reservoir capacity is required. The required capacity for the reservoir at Ero-Omola was evaluated using sequent peak algorithm. Linsely et al (1992) and Louck and Sigvaldson

(2004) described the use of sequent peak algorithm stating that values of cumulative sum of inflow minus withdrawal including average evaporation and seepage are calculated. The first peak local maximum of cumulative net inflow and the sequent peak (next following peak that is greater than the first peak) are identified. The required storage for the interval is the difference between the initial peak and the lowest trough in the interval. The process is repeated for all cases in the period under study and the largest value of the required storage can be found.

2.4 Simulation

The sequential stream flow routing method sequentially computes the energy output at a specified interval in the period of analysis. A continuity equation is used to route the stream along the natural channels, taking into account the variations in reservoir elevation as a result of the inflow simulations. Use of the sequential routing in the continuity equations allows the simulation of the hydropower, but also includes flood control operation, irrigation and water supply operation. This system is based upon continuity equation given as:

$$\Delta S = I - O - L \tag{6}$$

Where AS=change in reservoir storage (m^3)
I = Reservoir Inflow (m^3)
O = Reservoir outflow (m^3)
L = Sum of the losses due to evaporations, diversions, etc. (m^3)

The sequential stream flow routing method can be applied to basically any type of flood analysis. These include run-off-the river projects; run-off-the river project with pondage; flood control project only; storage regulated for power only; and storage regulated for multi-purpose, including power, peaking hydro-projects and pumped storage hydro-projects. The basic type of data needed are the historical stream flows and other information from the flow duration analysis. The basic steps for this procedure are (US Army Corps of Engineers, 1995):
Step 1-Select plant capacity
Step 2-Compute stream flow available for power generation
Step 3-Determine average pond elevation
Step 4- Compute net head
Step 5- Estimate efficiency
Step 6-Compute generation
Step 7-Compute Average Annual Energy

To perform the routing, the continuity equation is expanded as:

$$\Delta S = I - (Q_p + Q_L + Q_S) - (E + W) \quad (7)$$

Where Q_p =Power Discharge

Q_S =Overflow or spill

Q_L = Leakages or waste

E = Net Evaporation Losses (Evaporation –Precipitation)

W = Withdrawal for water supply, irrigation, recreation etc.

the rate of storage ΔS for a given time interval can be defined as;

$$\Delta S = \frac{(S_{t+\Delta t} - S_t)}{C_S} \quad (8)$$

Where St = beginning of period of storage

$S_{t+\Delta t}$ = end of period of storage

Δt = is the storage or routing period (30days, 7days, 1day, 1hour)

Cs = Discharge to storage conversion factor

Substituting (8) in (7) and rearranging gives

$$S_{t+\Delta t} = S_t - C_s [I - Q_p - Q_L - Q_S - (E + W)]$$

$$\text{Or} \quad S_2 = S_1 - C_s[(I - Q_p - Q_L - Q_S - (E + W)] \quad (9)$$

3. Results and discussion

3.1 Rating Equations and Streamflow Extension

The twelve rating equation developed using the recorded data on gauge heights and the corresponding measured discharges between Januarys to December is presented below. The discharge generated from the Rating equations is presented in Table 1, while the extended monthly discharges from 2009-2017 are presented in Table 2.

$$Q = 9.206\, H^{0.491} \quad (10)$$

$$Q = 9.253\, H^{0.765} \quad (11)$$

$$Q = 9.089\, H^{0.934} \quad (12)$$

$$Q = 10.496\, H^{1.049} \quad (13)$$

$$Q = 10.229\, H^{1.455} \quad (14)$$

$$Q = 8.539\, H^{2.258} \quad (15)$$

$$Q = 0.610\, H^{7.789} \quad (16)$$

$$Q = 12.65\, H^{1.517} \quad (17)$$

$$Q = 25.308\,H^{0.400} \tag{18}$$

$$Q = 1.166\,H^{5.505} \tag{19}$$

$$Q = 17.167\,H^{2.753} \tag{20}$$

$$Q = 1.617\,H^{5.977} \tag{21}$$

Table 1: Ero-Omola daily discharge data generated from rating equations

Day	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov.	Dec.
1	6.177	4.908	3.220	5.285	4.399	16.815	6.690	9.710	25.104	6.596	40.024	6.436
2	6.177	4.866	3.580	5.285	15.320	15.983	5.961	9.188	25.001	6.083	39.219	5.849
3	6.177	4.846	3.526	5.179	14.816	14.389	4.997	30.337	29.118	5.375	36.102	5.052
4	6.143	4.977	3.491	5.072	14.317	13.132	4.172	29.821	28.787	4.538	33.148	4.573
5	6.143	4.941	3.437	7.111	13.014	11.029	3.468	29.821	28.620	3.810	31.037	4.132
6	6.143	4.905	3.384	6.895	12.219	7.4255	2.692	28.546	28.280	9.363	29.013	3.538
7	6.143	4.887	3.313	6.572	9.785	6.563	2.072	27.040	27.131	8.352	26.449	3.017
8	6.143	4.869	3.259	6.464	9.639	5.916	1.474	26.298	27.131	7.144	26.139	1.347
9	6.143	4.832	3.187	6.464	9.493	5.305	3.258	24.113	28.704	6.083	24.623	1.117
10	6.143	4.260	3.134	6.356	9.932	4.872	2.692	22.928	28.451	5.155	23.452	0.920
11	6.143	4.225	3.845	6.141	9.348	13.878	1.811	21.995	28.194	4.161	15.342	0.656
12	6.143	4.172	3.736	6.034	8.917	13.378	1.375	21.303	28.021	3.563	14.058	0.530
13	6.143	4.119	3.626	5.927	8.492	12.408	0.376	19.275	27.492	2.900	12.074	0.395
14	6.143	4.084	3.535	5.713	8.352	11.252	0.318	16.051	32.646	2.285	12.074	0.289
15	6.110	4.013	3.205	5.392	7.937	10.589	0.318	15.431	32.438	2.071	11.700	0.246
16	6.110	4.959	3.187	5.179	7.527	6.563	0.097	12.078	32.087	0.931	10.974	0.208
17	6.110	4.814	3.152	7.653	9.932	5.916	0.064	11.331	30.845	0.879	30.353	0.147
18	6.110	4.704	3.718	7.328	9.639	7.971	19.479	0	30.466	0.781	27.712	0.102
19	6.110	4.365	3.827	6.356	9.348	7.073	12.262	0	30.000	0.576	25.831	3.926
20	6.110	4.209	3.736	6.249	8.917	6.316	9.891	9.710	29.604	0.446	22.880	3.183
21	6.110	4.030	3.663	8.305	8.352	20.068	6.316	8.846	29.604	4.161	15.786	1.433
22	6.110	4.866	3.590	8.087	8.213	18.549	4.997	8.677	30.234	3.810	14.478	1.266
23	6.110	4.783	3.498	9.836	7.937	17.670	3.690	8.677	29.843	3.329	13.241	1.117
24	6.110	4.741	3.442	9.288	7.799	16.535	2.364	8.342	29.684	2.900	11.700	0
25	6.110	4.699	3.294	8.741	7.527	15.174	1.580	24.353	29.282	2.639	10.278	0

Table 2: Projected Mean Monthly Streamflow Dischages(m^3/s) Data For Ero-Omola (2009-2038)

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
January	6.049	6.074	6.100	6.125	6.150	6.176	6.201	6.226	6.252	6.278	6.303	6.329	6.355	6.381	6.407	6.433	6.459	6.485	6.511	6.537
February	4.939	3.610	3.957	4.338	4.755	3.475	3.810	4.177	4.578	5.018	5.500	6.028	6.606	4.827	3.528	3.868	4.240	4.648	5.094	5.583
March	3.755	3.423	3.122	2.847	2.597	3.001	3.465	4.001	4.618	4.209	3.837	3.498	3.189	2.909	2.654	2.421	2.504	2.589	2.677	2.767
April	12.840	12.223	11.635	11.076	10.544	10.038	10.405	10.786	11.1808	11.589	12.013	12.452	12.907	13.379	13.867	14.374	14.899	15.443	16.006	16.591
May	19.648	20.021	20.399	20.786	21.180	21.582	21.991	22.408	22.833	23.266	23.707	24.156	24.614	25.081	25.556	26.041	26.534	27.037	27.550	28.072
June	21.391	21.910	22.441	22.985	23.541	24.111	24.693	25.289	25.899	26.524	27.163	27.816	28.485	29.170	29.870	30.587	31.320	32.071	32.839	33.625
July	24.097	25.941	27.927	30.064	32.364	34.840	20.838	12.464	14.165	16.098	18.295	20.790	23.625	26.846	30.506	34.665	39.390	44.758	34.798	39.541
August	36.955	39.537	40.677	41.850	43.056	44.296	45.571	46.883	38.589	31.765	32.685	33.631	34.604	35.604	36.632	37.690	38.778	39.897	36.955	39.537
September	49.071	45.150	41.542	38.224	38.687	39.156	39.631	40.111	40.597	41.089	41.587	42.090	42.600	43.116	43.638	44.166	44.701	45.242	45.790	46.344
October	39.917	42.858	46.015	42.858	46.015	49.404	46.015	32.937	35.365	37.971	40.768	43.771	46.995	46.883	38.589	36.632	37.690	38.778	39.897	36.955
November	32.307	33.242	34.204	35.193	36.210	37.256	38.331	39.437	40.575	41.745	42.948	44.185	45.458	46.766	48.112	37.126	33.425	37.838	38.741	39.664
December	19.979	19.852	19.725	19.600	19.475	19.352	19.230	19.108	18.988	18.868	18.750	18.632	18.515	18.400	18.285	18.171	18.058	17.946	17.835	17.724

Months	2029	2030	2031	2032	2029	2030	2033	2034	2035	2036	2037	2038
January	6.857	6.884	6.911	6.938	6.857	6.884	6.965	6.993	7.020	7.048	7.075	7.020
February	7.458	8.172	8.954	9.811	7.458	8.172	10.750	11.778	12.903	14.137	15.487	12.903
March	4.101	4.236	4.375	4.518	4.101	4.236	4.666	4.819	4.976	5.139	5.306	4.976
April	25.500	26.430	27.393	28.391	25.500	26.430	29.425	30.498	31.609	32.760	33.953	31.609
May	35.164	35.831	36.510	37.201	35.164	35.831	37.906	38.624	39.356	40.101	40.861	39.356
June	44.614	45.675	46.760	47.870	44.614	45.675	49.006	50.169	51.359	52.576	53.822	51.359
July	27.497	31.245	20.556	23.360	27.497	31.245	26.545	30.164	34.276	38.948	44.256	34.276
August	36.955	39.537	40.677	41.850	36.955	39.537	30.835	31.419	32.014	32.621	33.239	32.014
September	53.537	54.184	54.839	55.501	53.537	54.184	56.172	56.851	57.538	58.233	58.936	57.538
October	36.533	37.405	38.298	39.211	36.533	37.405	40.145	41.101	42.080	43.081	44.106	42.080
November	52.576	53.822	36.738	37.615	52.576	53.822	38.512	39.430	40.370	41.331	42.315	40.370
December	16.468	16.369	16.270	16.172	16.468	16.369	16.075	15.979	15.884	15.789	15.695	15.884

3.2 Reservoir Elevation - Storage Computation

The reservoir elevation - storage computation is presented in Table 3 and the elevation – capacity and elevation – area curves are given in Figure 2.

Table 3: Reservoir Elevation Storage Computation

Contour	Area Enclosed	Average Area	Height Between Contour	Volume Between Contour	Volume Up to Contour
	m^2 (10^3)	m^2 (10^3)	m.	m^3	m^3 (10^6)
450	0				0
451	2.4	1.2	1	1.2	1.2
452	7.9	3.95	1	3.95	5.15
453	35	17.5	1	17.5	22.65
454	57	28.5	1	28.5	51.15
456	89	44.5	1	44.5	95.65
457	159	79.5	1	79.5	175.15
458	243	121.5	1	121.5	296.65
459	361.2	180.6	1	180.6	477.25
460	434	217	1	217	694.25
461	490.5	245.25	1	245.25	939.5
462	510.7	255.35	1	255.35	1194.85
463	645	322.5	1	322.5	1517.35
464	761	380.5	1	380.5	**1897.85**

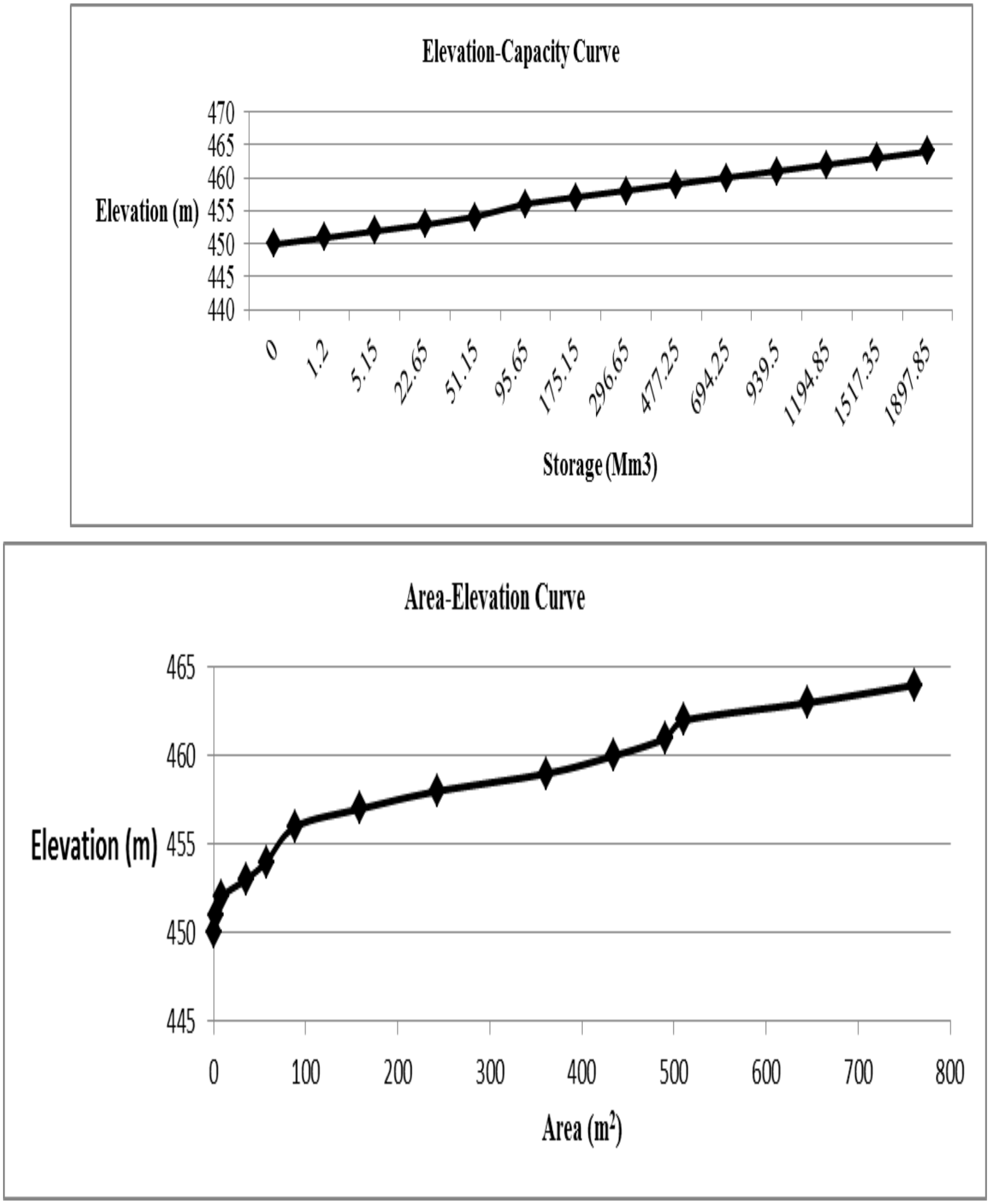


Figure 2: Elevation - Capacity and Elevation- Area Curve

3.3 Flow Duration Curve

Twenty years of streamflow records (2009-2028) were utilized. The streamflow data was arranged in ascending order. The percentage of exceedence and annual projected hydropower generation potential were computed as shown in Table 4. The Flow Duration Curve as well as the Power Duration Curve are plotted as shown in Figures 3 and 4.

Table 4: Computation of Flow Duration Curve Using 20 years of Data

No.	Year	Flow(m^3/s)	Flow in Ascending Order	Power=9.81QHe (kw)	% of time of availability $\frac{N+1-n}{N}(\%)$
1	2009	22.57	21.97	12789.18	100
2	2010	22.82	21.98	12795	95
3	2011	23.14	22.03	12824.1	90
4	2012	22.99	22.57	13138.45	85
5	2013	23.71	22.79	13266.51	80
6	2014	24.39	22.82	13283.98	75
7	2015	23.34	22.99	13382.94	70
8	2016	21.98	23.14	13470.26	65
9	2017	21.97	23.34	13586.68	60
10	2018	22.03	23.61	13743.85	55
11	2019	22.79	23.71	13802.07	50
12	2020	23.61	24.34	14168.8	45
13	2021	24.49	24.39	14197.91	40
14	2022	24.94	24.49	14256.12	35
15	2023	24.8	24.8	14436.58	30
16	2024	24.34	24.83	14454.04	25
17	2025	24.83	24.94	14518.07	20
18	2026	26.06	25.39	14780.03	15
19	2027	25.39	26.06	15170.05	10
20	2028	26.07	26.07	15175.87	5

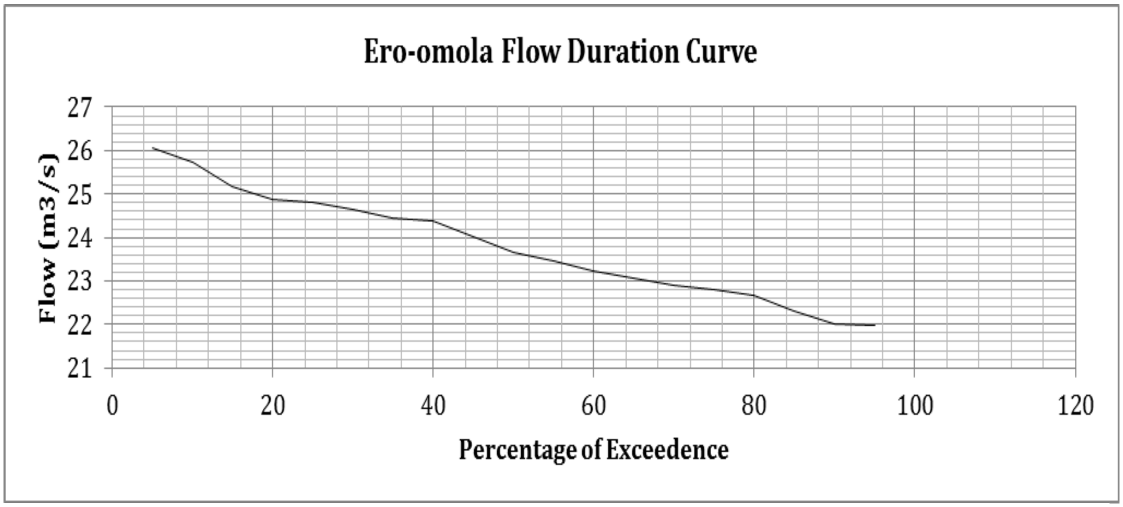


Figure 3: Ero-Omola Flow Duration Curve

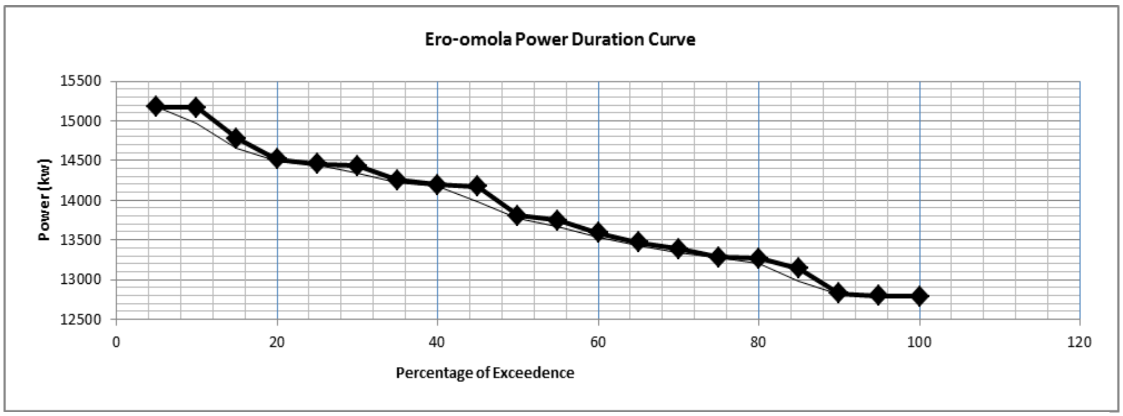


Figure 4.: Ero-Omola Power Duration Curve

3.4 Sequent Peak Algorithm Computation

Input to sequent peak algorithm computation consists of hydropower water demand, municipal water supply, irrigation water requirement, ecological water requirement, point rainfall, evaporation and runoff. The various requirements are:

a) Hydropower Water

From the flow duration curve Figure 3, 100% dependable hydropower demand flow was estimated at 21.80m^3/s. The hydropower releases for all year round generation is approximately 21.00m^3/s. The yearly demand is computed thus:

Yearly demand = 24 x 3600 x 365 x 21.00 = 662.256 x $10^6 m^3$

b) Municipal Water Supply Requirement

Estimated total water requirement for the benefiting communities within the three LGAs with a population of 172,207 (NPC, 2007) =46,495.89m^3/day

A daily dependable release is estimated as;

$46{,}495.89m^3/day \ = \frac{46{,}495.89}{24 \times 60 \times 60} \ = \ 0.538m^3/s$

Total Annual Supply: $0.538m^3/s$ x 24 x 60 x 60 x 365 =$16.966 \times 10^6 m^3$

c) Irrigation Water Requirement

Gross Area =480 ha

The water requirementis:$43.07m^3/ha/day$=$20673.6m^3/day$ =

$\frac{20673.6}{24 \ x \ 60 \ x \ 60} = \ 0.2392 \ \ or \ 0.24m^3/s$

$0.24m^3/s$ x 24 x 60 x 60 x 365 = $7.568 \times 10^6 m^3$ annually.

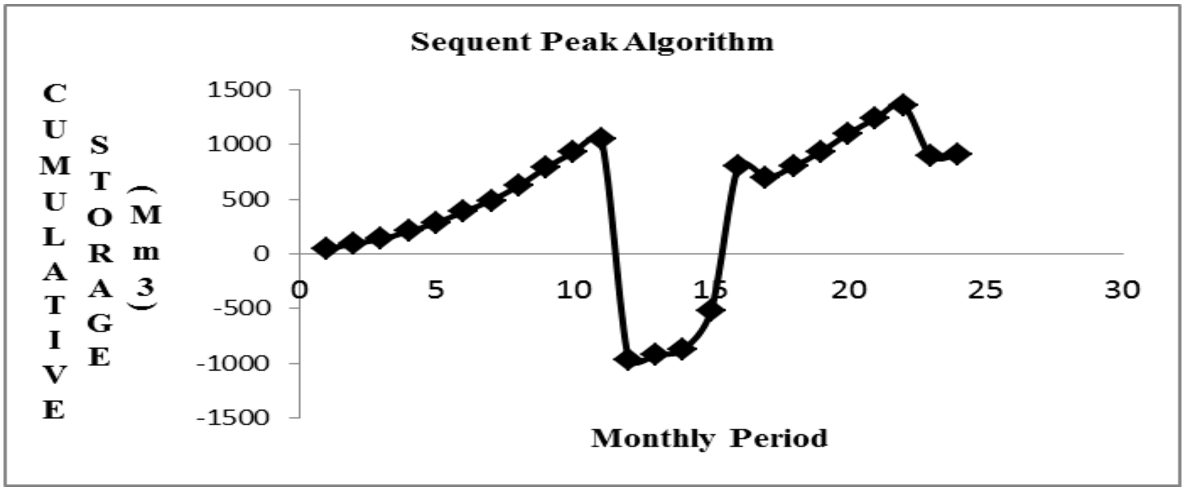
d) Ecological Water Requirement

The ecological water releases = $1.6 \times 10^{-3} m^3/s$ x 60 x 60 24 x 30 = $4.1472 \times 10^{-3} Mm^3$/Month or 50.366 Mm^3/annum based on the average wash bores and tube wells recharge rate of 1.6 l/s, in Fadama areas downstream of tailrace channels (FMWR, 2007).

The sequent peak algorithm is based on the above and data on rainfall, evaporation for the area and was used to determine reservoir storage to meet the demand of the system for hydropower, water supply, irrigation, ecological releases and losses. The detail computation is indicated in Table 5 and Figure 5.

Table 5: Reservoir Capacity Simulated with Sequent Peak Algorithm

Month	Monthly flow Q(Mm^3)	Hydropower water Demand(Mm^3)	Evaporation (Mm^3)	Ecological release (Mm^3) X 10^3	Irrigation Water Requirement(Mm^3) X 10^{-4}	Municipal water supply	Direct Rainfall (Mm^3)	Change in storage Q-D (Mm^3) (9)	Cumulative Storage (Mm^3)	Reservoir capacity (Mm^3)
1	2	3	4	5	6	7	8	(2)+ (8) -(3)- (4)-(5)-(6)-(7)	10	11
Jan.	16.201	58.39	0.095	4.147	8.4	1.440	0.005	44.890	44.890	
Feb.	12.371	52.73	0.123	4.147	6.5	1.348	0.008	48.689	93.579	
Mar.	10.057	58.39	0.147	4.147	3.4	1.440	0.031	43.721	137.299	
April	33.281	56.51	0.135	4.147	1.5	1.394	0.058	70.811	208.110	
May	52.622	58.39	0.121	4.147	2	1.440	0.092	87.773	295.883	
June	55.445	58.39	0.120	4.147	0	1.394	0.110	92.662	388.544	
July	64.541	58.39	0.091	4.147	0	1.440	0.082	101.712	490.256	
Aug.	98.98	58.39	0.086	4.147	0	1.440	0.070	136.144	626.400	
Sept.	127.192	56.51	0.092	4.147	2	1.394	0.138	164.344	790.744	
Oct.	106.913	58.39	0.100	4.147	3.8	1.440	0.092	140.285	931.029	
Nov.	83.739	56.51	0.102	4.147	6	1.394	0.015	116.758	1047.787	P1
Dec.	53.511	58.39	0.097	4.147	8.6	1.440	0.006	82.000	-965.788	
Jan.	16.2	58.39	0.095	4.147	8.4	1.440	**0.005**	44.889	-920.899	
Feb.	12.371	52.73	0.123	4.147	6.5	1.348	**0.008**	48.689	-872.210	
Mar.	10.06	58.39	0.147	4.147	3.4	1.440	**0.031**	43.724	-828.486	
April	33.28	56.51	0.135	4.147	1.5	1.394	**0.058**	70.810	-518.677	T1
May	52.62	58.39	0.121	4.147	2	1.440	**0.092**	87.771	606.447	
June	55.45	58.39	0.120	4.147	0	1.394	**0.110**	92.667	699.114	
July	64.54	58.39	0.091	4.147	0	1.440	**0.082**	101.711	800.824	
Aug.	98.98	58.39	0.086	4.147	0	1.440	**0.070**	136.144	936.969	
Sept.	127.19	56.51	0.092	4.147	2	1.394	**0.138**	164.342	1101.311	
Oct.	106.91	58.39	0.100	4.147	3.8	1.440	**0.092**	140.282	1241.593	
Nov.	83.739	56.51	0.102	4.147	6	1.394	**0.015**	116.758	1358.351	P2
Dec.	53.511	58.39	0.097	4.147	8.6	1.440	**0.006**	82.000	900.350	



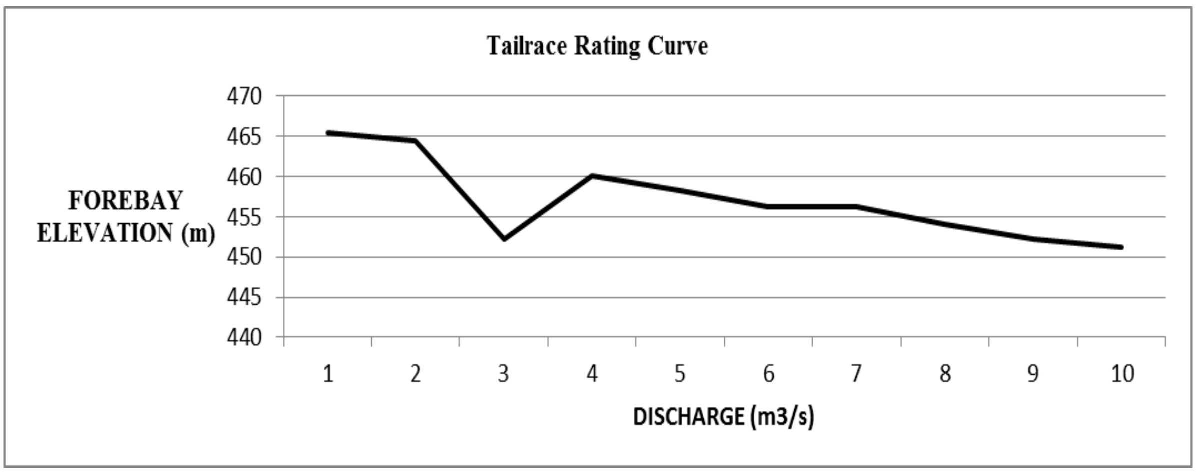


Figure 6: Tailrace Rating Curve

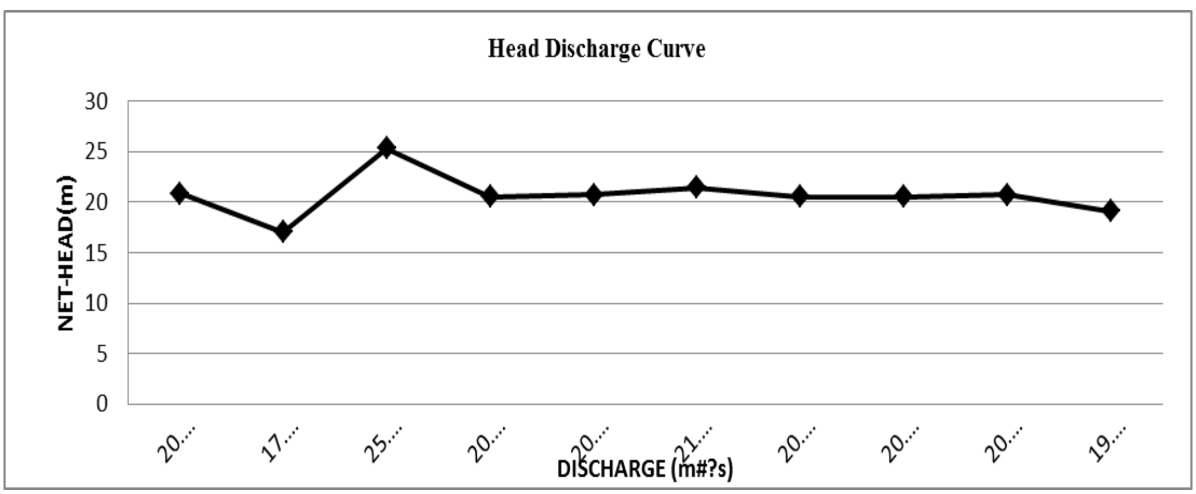


Figure 7: Head Discharge Curve

3.4 Simulation Results

The objective of simulation is to optimize potential firm energy. The simulation procedure is presented below while the results are shown in Table 6.

(1) **Critical Period** (Column 1 and 2)**:** The critical drawdown period has been defined as the seasonal cycle between the period when the reservoir is empty and when it is refilled to full capacity. Or the period during which all usable storage would have been fully drafted for optimum generation. The length of the critical drawdown period would be 29 months, (September -January)

(2) **Average Streamflow** (Column 3)**:** From the flow records, the average discharge into Ero-Omola reservoir during the critical drawdown period was found to be 21.39m^3/s.

(3) Net Reservoir Evaporations Loss: Evaporation = {19.44 x 10^6 m^2 x 150mm/1000 x 0.75} = 2.187 (Mm^3) or 2.187Mm^3/24x60x60x30=0.844m^3/s (column 4)

(4) Consumptive Withdrawals and Demands: (Column 5). Irrigation and Water Supply 0.24m^3/s + 0.538m^3/s = 0.778m^3/s {section 3.4(a) and (b)}.

(5) Net Reservoir Inflow. Given the reservoir inflow in (Column 3), evaporation rate, and reservoir withdrawal in (Column 5), then the net reservoir inflow for the same period is Net inflow = I - E – W = 49.071+ 0.8437m^3/s) – 0.778m^3/s =49.137m^3/s.(Column 6).

(6) Annual Energy (Column 7), is computed as $P = pgQHeT$ = P = 9.81 x 21 x 57.63 x 0.85 x 24 x 365 =8839272.486KWh/12 =736385.037 KWh. This value is distributed on monthly bases in accordance to demand allocation. (Column 7)

(7) Average Pool Elevation: (Column 8). The reservoir elevation over the critical drawdown period is approximated as 50% of the usable storage. The storage at the top of Forebay is 1420m^2 and the storage at the bottom of Reservoir is 25m^2

The total reservoir storage at 50% usable storage is estimated as:

$\frac{1420+25}{2} = 722.5m^2$ The pool elevation at 50% usable storage is found to be El. 455.21m

(8) Hydraulic Net Head: (Column 9). The net head corresponding to successive average pool elevation in column 8 is estimated from tailwater rating curve in Figure 6 and head discharge curve in Figure 7.

(9) Determine Required Power Discharge. (Column10). The firm energy requirement for September, 2009 was found to be 736385.037 kWh. The required power discharge would be computed as follows;

$$Q_P = \frac{(736385.037 \text{ kWh}/month)}{(9.81 \; x \; 49.83 \; x \; 0.85 \; x \; 30 \; x \; 24)} = 24.146 \; m3/s.$$

This value is inserted in Column 10.

(10) **Minimum Discharge for Downstream Requirement:** (Column 11). Ecological water requirement is presented in column 11 as 4.2 x $10^{-3}m^3/s$. per month.

(11) **Total Discharge.** (Column12). The total required discharge is the sum of the power discharge needed to meet firm energy (Q, Column 10) plus estimated leakage losses (Q_L = $2.5m^3/s$) . If this value exceeds the required power discharge plus losses, it would serve as the total discharge requirement. For the month of September, the minimum discharge requirement is $26.646m^3/s$, so the power discharge requirement establishes the total discharge requirement (Column 12). Qp + 2.5.

(12) **Compute Change in Storage.**(column 13)**.** The change in reservoir storage is a function of net inflow (Column 6), total discharge requirements (Column 12), at the start-of-month, reservoir elevation (Column 16 for the previous month). The difference between the net reservoir inflow and the total discharge requirement would establish whether the reservoir would draft, fill, or maintain the same elevation. This computation represents the solution of the continuity equation, which, when rearranged, would be as follows;

$$\Delta S = (I - E - W) - (Q_P + Q_L) \qquad (22)$$

For the month of September ΔS = $22.491m^3/s$

$$\Delta S = (49.137m3/s) - (26.646m3/s) = (22.491m3/s).$$

The ΔS value would be converted to 10^6m^3 using the discharge-to-storage conversation factor (C_S) for 30-day month,

$$\Delta S = (22.491 \text{ x } 24 \text{ x } 60 \text{ x } 60 \text{ x } 30.) = 58.296 \text{ x } 10^6 m^3$$

These values are inserted in Columns 13 and 14. For those months where net inflow exceeds total discharge requirements, the reservoir would store the difference unless it is already at the top of forebay pool. If the reservoir is full, the full net inflow (minus losses) would be discharged through the powerhouse, if possible over and above the firm energy requirement (Column 7)

(13) **Compute End-of-Month Reservoir Status** (Column 15)**.** The change in storage, ΔS, can also be expressed as follows:

$$\Delta S = S_2 - S_1$$

where: S_1=start-of-period storage volume

S_2 = end-of-period storage volume

The change in reservoir storage would be applied to the start-of-month storage volume (Column 15) of preceding month to determine the end-of-month storage volume. The end-of-month reservoir elevation was obtained from the storage-elevation curve (Table 3 and Figure 2). For September, 2012;

$$S_2 = S_1 + \Delta S = 1800Mm3 + (58.296Mm3) = 1858.296Mm3$$

From Figure 2, the end-of-month reservoir elevation is found to be El. 454.50m.

(14) **Reservoir Elevation at the End of Critical Drawdown: (column 16):** This is obtained from the storage-elevation curve or from column 15.

(15) **Compute Total Generation (Column 18):** During the critical period, generation will be limited to meeting firm energy requirements. The generation is computed by applying the net head (Column 9) to the greater of the required power discharge or the water quality requirement (Column 11) minus 2.5 m^3/s losses. For September 2009, the generation would be:

$$\left(\frac{24.1469m3}{s}\right)(49.83m)\,(24\ x\ 30hours)\ = 736385.036\ kWh,$$

Which is, of course, equal to the firm energy requirement for the month of September as calculated in step 6.

TABLE 6 : Simulated Sequential Streamflow Routing for Optimization of Potential Hydropower Development

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
RI														S2=1858.296			
MONTH	YEAR	(m3/s)	(m3/s)	(m3/s)	(m3/s)	MWh	(m)	(m)	Qp(m^3/S)	(m^3/S)	(m3/S)	(m^3/S)	(mcm)	(mcm)	Elevation	m^2	
August	2009	-	-	-	-	-	-	-	-		S1=1800.00			1800	461.5	1420	
							START OF CRITICAL PERIOD										
September	2009	49.071	-0.844	0.778	49.137	736385.037	461.5	49.83	24.147	4.2	26.64697	22.490	58.293	1858.293	460.03	1410.79	736385.037
October	2009	39.917	-1.086	0.778	40.225	442007.825	461.2	49.39	14.623	4.2	17.123	23.101	59.879	59.879	459.71	1303.45	442007.825
November	2009	32.307	-1.2937	0.778	32.823	442007.825	461.1	49.39	14.623	4.2	17.123	15.700	40.693	1898.987	459.05	1261.23	442007.825
December	2009	19.979	-1.1925	0.778	20.394	736385.037	461	49.39	24.362	4.2	26.862	-6.469	-16.767	43.113	458.8	1209.17	736385.037
January	2010	6.074	0.8437	0.778	4.452	736385.037	460.5	54.36	22.135	4.2	24.635	-20.182	-52.313	1846.674	457.91	1176.12	736385.037
February	2010	3.61	1.0856	0.778	1.746	442007.825	459.01	54.39	13.279	4.2	15.779	-14.032	-36.372	6.740	457.45	1125.04	442007.825
March	2010	3.423	1.2937	0.778	1.351	442007.825	459	44.06	16.392	4.2	18.892	-17.541	-45.466	1801.208	457.17	1043.76	442007.825
April	2010	12.223	1.1925	0.778	10.253	442007.825	458.91	53.02	13.622	4.2	16.122	-5.869	-15.214	-8.473	457.1	1011.19	442007.825
May	2010	20.02	1.0687	0.778	18.173	736385.037	458.45	51.86	23.202	4.2	25.702	-7.528	-19.514	1781.694	457	975.84	736385.037
June	2010	21.91	-0.0575	0.778	21.190	736385.037	458.11	51.19	23.505	4.2	26.005	-4.816	-12.483	-20.956	456.02	916.01	736385.037
July	2010	25.941	-0.8044	0.778	25.967	1473654.09	458.01	52.18	46.147	4.2	48.647	-22.679	-58.785	1722.910	455.98	779.84	1473654.089
August	2010	39.537	-0.7594	0.778	39.518	1473654.09	457.81	50.97	47.242	4.2	49.742	-10.224	-26.500	-47.456	455.17	722.51	1473654.089
September	2010	45.15	-0.8437	0.778	45.216	736385.037	457.53	49.83	24.147	4.2	26.647	18.569	48.130	1771.040	454.85	709.92	736385.037
October	2010	42.858	-1.0856	0.778	43.166	442007.825	457.29	49.39	14.623	4.2	17.123	26.042	67.502	20.046	454.67	678.45	442007.825
November	2010	33.242	1.2937	0.778	31.170	442007.825	457.29	49.39	14.623	4.2	17.123	14.047	36.410	1807.450	454.32	643.26	442007.825
December	2010	19.852	1.1925	0.778	17.882	736385.037	457.17	49.39	24.362	4.2	26.862	-8.981	-23.278	-3.231	454.12	601.57	736385.037
January	2011	6.1	0.855	0.778	4.467	736385.037	457	54.36	22.135	4.2	24.635	-20.168	-52.275	1755.176	453.81	575.18	736385.037
February	2011	3.957	0.855	0.778	2.324	442007.825	456.41	54.39	13.279	4.2	15.779	-13.455	-34.875	-38.106	453.48	534.07	442007.825
March	2011	3.122	0.855	0.778	1.489	442007.825	456.21	44.06	16.392	4.2	18.892	-17.403	-45.109	1710.067	453.11	492.11	442007.825
April	2011	11.635	0.855	0.778	10.002	442007.825	456.13	53.02	13.622	4.2	16.122	-6.120	-15.863	-53.969	453	448.78	442007.825
May	2011	20.399	0.855	0.778	18.766	736385.037	455.96	51.86	23.202	4.2	25.702	-6.936	-17.978	1692.089	452	374.13	736385.037
June	2011	22.441	-0.855	0.778	22.518	736385.037	455.34	51.19	23.505	4.2	26.005	-3.487	-9.039	-63.009	451.94	328.19	736385.037
July	2011	27.927	-0.855	0.778	28.004	1473654.09	455.05	52.18	46.147	4.2	48.647	-20.643	-53.506	1638.584	451.81	269.11	1473654.089
August	2011	40.677	-0.855	0.778	40.754	1473654.09	455	50.97	47.242	4.2	49.742	-8.988	-23.297	-86.306	451.65	233.14	1473654.089
September	2011	41.542	-0.855	0.778	41.619	736385.037	454.86	49.83	24.147	4.2	26.647	14.972	38.808	1677.391	451.57	183.62	736385.037
October	2011	46.015	-0.855	0.778	46.092	442007.825	454.21	49.39	14.623	4.2	17.123	28.969	75.087	-11.219	451.39	151.41	442007.825
November	2011	34.204	-0.855	0.778	34.281	442007.825	453.73	49.39	14.623	4.2	17.123	17.158	44.473	1721.864	451.28	92.56	442007.825
December	2011	19.725	-0.855	0.778	19.802	736385.037	452.11	49.39	24.362	4.2	26.862	-7.060	-18.300	-29.518	451.25	41.87	736385.037
January	2012	6.125	-0.855	0.778	6.202	736385.037	451.91	54.36	22.135	4.2	24.635	-18.433	-47.778	1674.087	451	25.33	736385.037
									END OF CRITICAL PERIOD								
	SUM	701.983	3.859	27.562	670.562	20771722.73	13266	1481	666.448	132.8	750.947	-59.966	-155.432	26125.049			**20771715.732**
	AVERAGE	23.399	0.128	0.919	22.353	692390.758	442.19	49.38	22.981	4.427	25.031	-2.068	-5.360	900.864			716266.060

RI= ROUTING PERIOD/INTER 2= YEAR 3= INFLOW 4=EVAPORATIONS 5=WITHDRAWALS 6=NET-INFLOW 7=ENERGY REQUIREMNT 8=AVERAGE POOL ELEVATION 9=NET-HEAD 10=REQUIRED PEAK DISCHARGES
11=ECOLOGICAL WATER RELEASES 12=TOTAL DISCHARGE FOR DOWNSTREAM REQUIRMENT 13=CHANGE IN STORAGE(ΔS) (m3/S) 14= EQUIVALENT CHANGE IN STORAGE (ΔS) (mcm) 15=END OF PERIOD OF RESERVOIR STORAGE (S2)
16 = EIEVATION 17= RESERVOIR SURFACE AREA 18=TOTAL POWER GENERATIONS

16. Summary

The simulation was carried out on 'excel' with the above items as input. The reservoir simulation was based on the initial estimate of reservoir capacity of 1812 x $10^6 m^3$ at 2.7 x $10^3 m^3/s$ maximum inflow and dead storage of 1.8075 x $10^6 m^3$. The initial analytical estimates of potential hydropower was estimated at 8.01101MW, while annual generation potentials was estimated at 14035.272 MWh at hydraulic capacity of $21 m^3/s$.

The simulation result given in Table 6 however show that the potential power could be higher i.e P= 9.81 x 21 x 57.63 x 0.85 =10.091 MW while the annual energy of =18,401.56501 MWh was reached.

Hence the result indicated about 20.6% more potential hydropower, while annual energy was increased by additional 23.4%.

4 Conclusion

The major conclusions derived from the study are:

a) The theoretical potential hydropower generating capacity of Ero-Omola fall at 100% dependable flow of 80 years return period is estimated at 8.011MW. The annual average energy is estimated at 14035.272MWh.
b) The simulated potential hydropower generating capacity of Ero-Omola fall at 100% dependable flow of 80 years return period is estimated at 10,091.502MW. The annual average energy is estimated at 18,401.56501MWh
c) The simulation result indicated about 20.6% for more potential hydropower, while annual energy was optimized by 23.4%.
d) Water treatment plant capacity is estimated at 22,500 litres or $22.5 m^3/s$.
e) Irrigation water requirement is estimated at 2.2 x $10^6 m^3$ with peak irrigation water demand of $43.07 m^3/ha/day$.
f) The minimum ecological water requirement downstream is estimated at 1.6 x $10^{-3} m^3/s$, which would minimize or eliminate seasonal flooding downstream.

References

1. C. Punmia, and M. Pande, "Runaway potential: Small hydro in Europe and beyond". *Renewable Energy World*, pp. 248-253. July-August, 2008,
2. Department of Army Corps of Engineer, "Hydropower Design Manual", Vol.3, N^{o}, 125, 143-15, 1995.
3. F. Beard and A. Kumar, "Small hydroelectric power plants in Turkey". *Hydro 1999*. Kiriş-Turkey Vol. 4, N^{o} 12, pp. 283-293 June 1999.
4. Federal Ministry of Water Resources. "Guidelines for the sustainable development of Fadama areas of Kwara, Kogi, Niger and Federal Capital Territory in Nigeria", *World Bank Report,* (pp.453-454) 2007.
5. G. Loucks and M. Sigvaldson, "Small hydropower situation in the New EU member States and candidate Countries". *European Small Hydropower Association Journal,* Vol.7, N$^{o.}$74, 2004.
6. G.A. Nash, "Optimization of the operation of a two reservoir hydropower system". *Ph.D. Thesis,* Department of Civil Engineering. The University of British Columbia, Canada, pp.121, 1984
7. International Hydropower Association (IHA), "IHA Sustainability Guidelines". London. 2004.Availableat:http://www.hydropower.org/sustainable_hydropower/IHA_Sustainability_Guidelines.htm
8. J. A. Koch-Guibert, "The value of hydrologic information in stochastic dynamic programming models of a multireservoir system", *Water Resources Research,* Vol. 10, N^{o} 31, pp. 2571-2579. 1985.
9. J. Beard, "Hydropower: The design, use and function of hydromechanical", *Hydraulic and Electrical Equipment.* Dusseldorf: VDI-Verlag. Vol. 9, pp.102, 1982.
10. J. C Umolu, "Sustainable water management for energy production in the Niger Basin of Nigeria". Journal of Innovative Research in Engineering and Science, *Global Research Publication.*Vol.7, N^{o}.53, pp. 1419-1945.S.A 2006.
11. J. C. Zolgay, and J.R Stedinger, "Algorithms for optimizing hydropower systems". *Water Resources Research*, Vol.1, N^{o} 21, pp.1-10. 1991.
12. K. M. Labaide, "Optimal operation of multireservoir systems": *state of the art review. Journal of water Resources.* Plan Manage, Vol. 2 N^{o} 130, 93-111, 2004.
13. M. Chennani and S. Doubabi, "A simulation study of the regulation of a micro-hydroelectric power plant", *AMSE journals, Advances C,* Vol. 63, N^{o}4, pp.12-17, 2008.

14. M. Hingis, M.H. Houck, and J.W. Delleur, "Optimization and simulation of multiple reservoir systems". *Journal of Water Resources Planning and Management*.Vol.1, N^{o} 118, pp.71- 81, 2001
15. M. Karamouz, "Reservoir operation optimization: A nonstructural solution for control of seepage from Lar Reservoir in Iran". International Water Resources Association. *Water International*. Vol. 1, N^{o} 28, pp19-26. 2003.
16. P. R. Kelman, "An Introduction to linear programming and game theory". 2nd edition, *John Wiley & Sons*, NY, pp.97-99, 1980.
17. R. K. Linsley, J. B. Franzini, D. L Freyberg and G. Tchobanoglous,. "Water Resources Engineering. Singapore": McGraw-Hill, Inc. pp. 109, 1992.
18. T.A McMahon, and R. G Mein, "Reservoir capacity and yield", *Elsevier Scientific Publishing Company* Amsterdam. pp. 198, 1978
19. T.C.E Sharma, "Stochastic modeling of reservoir operations". European Journal of Operational Research, Vol. 3, N$^{o.}$50, pp. 235-248. 1979.