Available online at http://www.ajol.info/index.php/njbas/index
Nigerian Journal of Basic and Applied Science (December, 2012), 20(4): 341-348

ISSN 0794-5698

Full Length Research Article

Analysis of the Water Resources Potential and Useful Life of the Shiroro Dam, Nigeria

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ABSTRACT: Analysis of water resources potential and useful life of the Shiroro hydro reservoir was carried out with the view to assessing its current state, operations and management. Hydro-meteorological data was obtained from the hydrological Department of the Shiroro Hydropower project for the period of 16 years (1990 to 2006). Analysis of the data reveals that the month of April has the lowest inflow (1,281.7 million m^3). Analysis of the inflow and draft shows that the storage in the reservoir is inadequate to power all the four installed turbines, as a consequence of which only three are being used. The seepage through the dam was estimated to be 725.19 m^3/day and the useful life of the reservoir was estimated to be 137.7 years (1984 to 2122). Also, calculation reveals that to be able to meet the intended uses of the dam (600 MW output), a balance return flow through a pumped storage operation of 204.5 m^3/s would be required. Finally, suggestions were given as to the other possible ways to reduce siltation and enhance reservoir performance.
Keywords: Shiroro dam reservoir, water resources potential, useful life, hydropower, pumped storage.

INTRODUCTION

Water balance analysis is a highly effective tool that relates local climate, geological, hydrological and land use conditions to the quantity of water available for ground water recharge and surface runoff. It is therefore possible to quantitatively evaluate water resources and their changes under the influence of man's activities (Linsley and Kohler, 1992).

Where the surface water flow is collected through the receiving water body by the creation of an impounding reservoir, there is bound to be losses due to evaporation, absorption and seepage. This is apart from the other uses to which the impounded water is meant for, such as hydropower generation and releases for downstream requirement (Adie *et al*, 2008).

Shiroro reservoir is located at a distance of 365 km from the Jos-Plateau. The hydrology of River Kaduna has only one main period of peak flow, which falls between August and September. The catchment has an annual rainfall of about 1300 mm with an annual evaporation loss of between 2.48 $x10^8$ and $4.35x10^8$ m^3. The creation of the reservoir has led to a change of climatic conditions in and around the reservoir area. There is a remarkable cool zone in the reservoir area, while the southern part of the Shiroro Local Government Area is warmer. There is also a higher humidity in the reservoir area than in the southern parts (Sanyu and Sunmiko, 1995).

The Shiroro reservoir has a total installed capacity of 600MW, with four Francis turbines of 150 MW each (NEPA, 1984). Also, Shiroro Hydropower project depends on the water flow from the River Kaduna (70%) and four other principal and eight minor tributaries contributing to its summed total capacity of $8x10^9$ m^3 for the generation of electricity. It is important to appraise the current operational and management issues relating to water utilization and benefits.
The objective of this study is to perform a water balance analysis of the Shiroro reservoir and to appraise its sedimentation status.

MATERIALS AND METHODS

Precipitation

The manual rain gauge was used for the collection of rain, which is measured each day at 9.30 am using a graduated glass cylinder. The meteorological station at Shiroro has daily and monthly rainfall data from 1990 to 2007.

Gauging and discharge measurement

The stage height for the river was measured directly using a staff gauge at 8.00am and 12.00 am respectively. The gauge heights were converted to discharge using a pre-prepared rating curve obtained by velocity area methods. Average monthly inflow into Shiroro dam records was available from 1990 to 2007.

Evaporation

The international Standard (I.S) pan is a modified version of U.S class A evaporation pan. Regular daily readings were taken at 10.30am. The average pan evaporation was converted to lake evaporation by multiplying by a factor of 0.8. The average monthly evaporation data was obtained from 1990 to 2006.

Other data obtained were humidity and temperature reading for the same period from 1990 to 2007.

Seepage analysis: the seepage data for the Shiroro dam was not available. But according to Nwugiofor (2006) the hydraulic conductivity (k) of the dam embankment was 1.13×10^{-7}m/s.

Therefore, the Darcy's law was used to calculate seepage as:

$$\Delta q = K(d_m x1)(\Delta h_1/dl) \quad (1)$$

Using the flow net method (fig. 1), since the flow net is a squared grid, the head drop is the same with the potential drop: $\Delta h_1 = \Delta h_2$ and $d_m = dl$. Similarly, if there are n such drops then $\Delta h = H/n$, where H= total head loss and n= no equipotential drops. If M is the number of channels in the net, then the total flow per unit width is:

$$q = (M/n)K(d_m/dl)H = (M/n)KH \quad (2)$$

Where;
q = rate of flow o seepage per unit width and
K = hydraulic conductivity

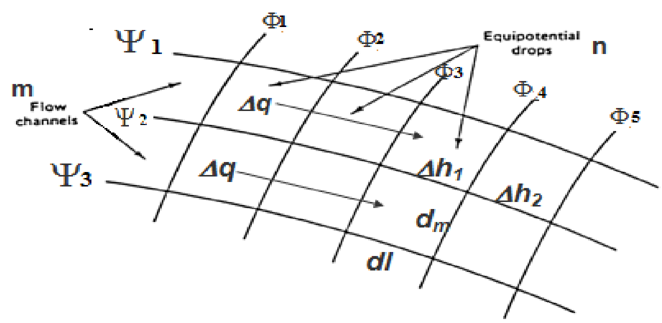

Figure 1: Flow net method of analysis with Streamlines Ψ and Equipotential lines ϕ

Computation of Shiroro Reservoir Useful Life

In order to compute the useful life of Shiroro reservoir, the sediment load data of Kaduna River as presented by Sanyu and Sunmiko Consultants (1995) is shown in Table 1.

Table 1: Annual Sediment Load of Kaduna River (Tons/year)

Month	Total Sediment Load (Tons)
May	1.066×10^7
June	6.8×10^7
July	2.13×10^8
August	7.107×10^8
September	1.244×10^9
October	1.031×10^9
November	2.594×10^8
December	1.638×10^7
Total	3.553×10^9

Source: Sanyu and Sunmiko Consultants (1995)

According to MRT Consulting Engineers (1979), the suspended sediment discharge in most Northern Nigeria rivers range from 220 tons/km^2 (1.2 g/l) to 740 ton/km^2 (7.3 mg/l) , which can be averaged to 420 tons/km^2 (4.0 g/l). It gave the relationship between the sediment yield per unit total run-off, S (g/l) and average annual rainfall, r (mm), which was plotted logarithmically and the exponential function fitted subjectively as:

$$S = e^{(-0.0124r + 11.81)} + 1.0 \quad (3)$$

The Kaduna River contributes over 70 % of the inflow; therefore, it was assumed that it contributes over 70 % of sediment inflow into the Reservoir. It was also assumed that the mass density of sediments was 1100 kg/m^3, with 100 percent trap efficiency, since the Dam does not spill (Adeogun, 2008, and U.S. Corps of Engineers, 1989a, b & 1995).

The total sediment deposit (3.55 x10^9 tons/year) was converted from weight unit to volumetric unit in mega hectare meter using the mass density of sediments. Then the useful life of the Reservoir was computed as in Table 4.

Analysis using equation (3) with an annual rainfall of 1300 mm and total inflow of 8 x 10^9 m^3 gives a total sediment load of 8.11 x 10^9 m^3/year, which is equal to 8.92 x10^9 tons/year.

Water budget analysis

The basic expression used for the water budget calculation was given by Dandenkar and Sharma (1979):

$$S_f = S_i + \text{Inflow (Rainfall + Runoff)} - \text{Outflow (Evaporation + Water for power generation)} \quad (4)$$

Where, S_f = Final storage and S_i = Initial storage

It was recommended that 3 m^3/s of water is required to generate 1 MW of power; for the reservoir capacity at any time to be able to cater for the electricity production, evaporation and the flow for downstream activities (Adie *et al*, 2008). The data was corrected to the same units of Million Cubic meters (MCM). The reservoir analysis was carried out with the assumption that it was full to capacity initially and produced maximum installed power production capacity at inception. As the analysis started with full storage capacity in January and successfully removed a turbine from operation each time the reservoir capacity reduced.

RESULTS

Discharge/Inflow

The data of discharge of the Shiroro reservoir was collected by the Hydrological Department of the Shiroro Hydropower Project (HDSHP) from their network of stations. The average daily discharge for each month is recorded in m^3/s. After analysis of the data collected from HDSHP the maximum value of mean discharge at Shiroro was 52,575 m^3/s in September 2003 and a minimum of 343 m^3/s in March 2002. The detailed record of these values was plotted in Figure 2.

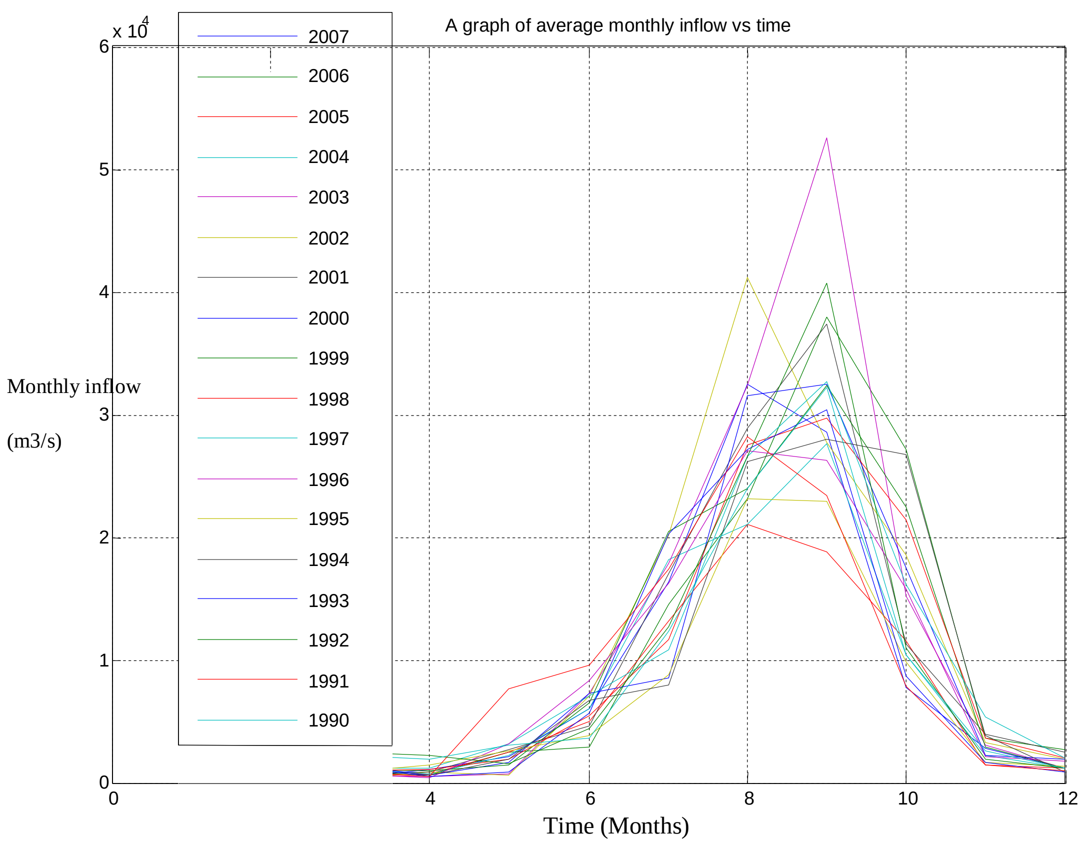

Figure 2: Average monthly inflow from 1990 - 2007

Rainfall

From the mean monthly rainfall data collected from the HDSHP, Niger State the years 1990 to 2006. The HDSHP station has a mean minimum of 0 mm in January and December of all the years and a mean maximum value of 473.2 mm in September, 1996 (Figure 3).

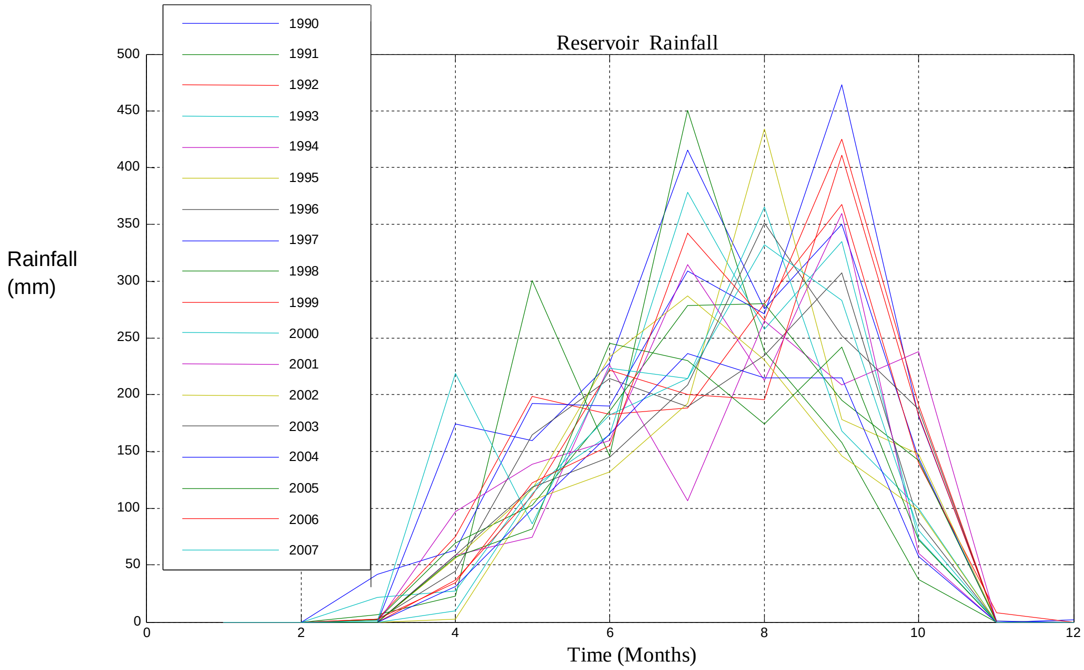

Figure 3: Average monthly rainfall from 1990 – 2007

Evaporation

The mean monthly evaporation data collected over the period from 1990 to 2006 showed minimum, mean and maximum values to be 5.8, 13.8 and 25 mm respectively as recorded in 2006 (Table 2).

Temperature and Relative Humidity

The mean monthly temperature and relative humidity data collected from the same station to ascertain the climatic change around the catchments revealed that from 1990 to 2007, the maximum temperature was 33^{o}C as recorded in 1998, while the minimum was recorded in 2004 and 2005 respectively as 18^{o} C. The highest monthly mean temperature of 28.8^{o} C was recorded in 1999. The relative humidity had a maximum value recorded as 98 mm for 1990 and reduced there from (Table 2).

Seepage Computation

To calculate the seepage through Shiroro reservoir using flow nets theory, the cross section of the dam structure, water elevations, and aquifer profile is drawn to scale as in Figure 4.

From the flow net, the total head loss, H is the operational maximum reservoir elevation minus tail water. Assume tail water to be zero, but the maximum crest height to foundation of 115m.
Therefore, H = 382 – 0 = 382 m

From the drawing, there are five flow channels (M) and 18 head drops along each flow path (n).
Therefore Q = (KM/n x H) x dam length.
But dam length = 700 m

From the seepage analysis,
K = 1.13 x 10^{-7} m/s = 0.00976 m /day.
Q = 0.00976 x 5/18 x 382 x 700 = 725.19 m^3/day

Volume of water that seeped through the dam each month is;
For 31days = 725.19 x 31 = 22,480.89m^3
For 30 days = 725.19 x 30 = 21,755.7m^3
For 29 days = 725.19 x 29 = 21,030.51 m^3
For 28 days = 725.19 x 28 = 20,305.32m^3

When the seepage values obtained are expressed in millions cubic meters, they become insignificant compared with the other components of the energy equation. It can then be concluded logically that the seepage through the embankment of the Shiroro dam can be neglected from the water balance computation.

Table 2: Values for Evaporation, Temperature and Humidity

	Monthly Evaporation (mm)			Monthly Humidity (mm)			Monthly Temperature (^{O}C)		
Year	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Mean**	**Minimum**
2006	25	13.8	5.8	91	74.1	38	26	22.4	21
2005	20	12.5	5.3	92	83.3	54	25	21.6	18
2004	19	10.6	4.4	91	68.9	26	26	23	18
2003	19	11.9	4.1	90	54.8	36	28	24.6	19
2002	24	10.9	4.9	90	53.2	23	29	25.8	23
2001	24	12.95	4.5	92	61.6	21	29	27.3	23
2000	18	10.8	4.8	93	74.1	21	32	28.1	25
1999	18	11.9	4.2	95	63	42	32	28.8	26
1998	22	11.6	3.9	97	72.7	44	33	28.7	23
1997	21	11.3	4	95	51.2	41	32	26.8	23
1996	23	12.4	4.2	95	73.3	37	31	28.6	24
1995	19	7.1	4	95	70.8	36	29	25.3	23
1994	18	10.4	4.7	97	71.5	41	31	27.8	23
1993	17	10.9	4	95	77.7	47	32	23.5	26
1992	20	10.8	4.9	96	68	43	32	28.1	26
1991	16	10	3.9	94	78.5	49	32	27.8	24
1990	15	10.5	4.9	98	75.3	54	31	23.1	24

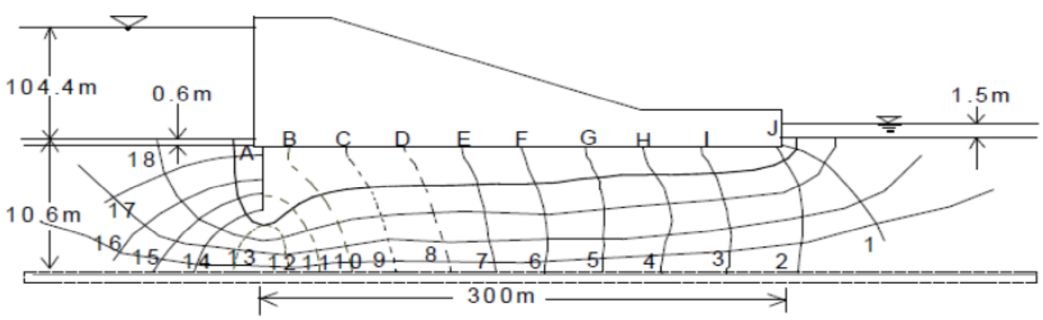

Figure 4: Flow Net Analysis of Shiroro Dam.

Water Budget Analysis

Table 3 show the analysis of the water budget as shown in equation 3, where all data were converted to compatible units.

It was noted by Adie *et al*. (2008), that 3 m^3/s of flow is needed to produce 1MW of power and when multiplied by the total power output given in megawatts gives the amount of water required to produce power per second. The reservoir was initially assumed to be full and the outflow variables i.e. evaporation and water for power were deducted from the inflow variables which are stream flow and rainfall. The net value of final storage showed how much would be left. This procedure was started using January as initial and taking each month with respect to the final storage of the previous month serving as the initial storage for the subsequent month. This analysis was based on the assumption that the reservoir is functioning in full capacity i.e. producing 600MW of power.

Storage Required

The total amount of hydroelectric power that would be made available from a stream depends on continuous flow rate of the stream and the head possessed by the flowing water. The Shiroro Reservoir has four Turbines which produce a total output of 600MW. The dam has a rated head of 97 m and a hydraulic head ranging from 70 - 110m.

If, Q, is the rate flow of water that may be continuously made available from the river and it had a head (H_m) in meters then the amount of hydropower, P, that would be available may be expressed as

$$p = H_m \rho g Q / \eta$$

Where: g = acceleration due to gravity η = overall efficiency, and ρ = density of water.

The overall efficiency of a hydroelectricity plant is equal to the hydraulic efficiency multiplied by the efficiency of the turbines and the generators. In most turbine and pump operations, the average value of the efficiency is about 80 to 90% (Modi and Seth, 1991).

$$Q = P\eta / g\rho H_m \quad (6)$$

$$Q = \frac{600x0.8}{9.81} x\ 1000\ x\ 70 = 699\ m^3/s$$

From the data collected the average minimum flow is as $Q_m = 494.5\ m^3/s$

The amount of water that would be required to be pumped back (Q_p) is the difference between the flow that is needed to produce the power (Q) and the minimum flow (Q_m)

$$Q_p = Q - Q_m \quad (5) \quad (7)$$

$$Q_p = 699 - 494.5 = 204.5 m^3/s$$

Estimation of Shiroro Reservoir Useful Life

Table 4 showed the estimation of the useful life of Shiroro reservoir. Analysis with the inflow from Kaduna River catchment which is 70% of the catchment gave a useful life of 196.72 years with a total sediment load of 3.553×10^9 tons/year. Taking the value for 100% catchment inflow, the useful life is 137.7 years (1984 to 2122). Catchment estimation gave a total sediment load of 8.92×10^9 tons/year.

Table 3: Water Budget for Shiroro Reservoir

Month	Mean Monthly Rain Over Reservoir (MCM)	Mean Monthly Inflow (MCM)	Mean Monthly Evaporation (MCM)	Water for Power (MCM)	Initial Storage (MCM)	Final Storage (MCM)	Water for Power (MCM)	Initial Storage (MCM)	Final Storage (MCM)
					600MW			450MW	
JAN.	0.00	4316.02	1439.09	4821.12	6500.00	4555.81	3615.84	6500.00	5761.09
FEB.	0.00	3203.13	1387.93	4510.08	4555.81	1860.93	3382.56	5761.09	4193.37
MAR.	1.40	3039.49	1335.55	4821.12	1860.93	-1254.85	3615.84	4193.73	2283.23
APR.	20.72	1281.74	865.85	4665.60	-1254.85	-3820.17	3499.20	2283.23	884.01
MAY	42.97	3715.99	622.89	4821.12	-3820.17	-5505.22	3615.84	884.01	404.24
JUN.	61.08	4001.06	447.60	4665.60	-5505.22	-6556.28	3499.20	404.24	519.52
JUL.	83.06	6638.37	435.83	4821.12	-6556.28	-5091.80	3615.84	519.52	3189.28
AUG.	86.85	7431.98	437.77	4821.12	-5091.80	-2832.06	3615.84	3189.28	6654.50
SEP.	87.52	8622.68	771.01	4665.60	-2832.06	441.48	3499.20	6654.50	11094.49
OCT.	38.16	4728.95	1021.51	4821.12	441.48	-634.04	3615.84	11094.49	11224.04
NOV.	0.17	4331.74	1171.85	4665.60	-634.04	-2139.58	3499.20	11224.04	10884.90
DEC.	0.00	4790.14	1530.80	4821.12	-2139.58	-3701.36	3615.84	10884.09	10528.40

Table 4: Estimation of Shiroro Reservoir Useful Life

		Trap Efficiency		Annual Trapped Sediment			
S/N	**Capacity (Mha-m)**	**Point efficiency (%)**	**Average efficiency (%)**	**Mass (kg)**	**Volume (Mha-m)**	**Incremental Vol. (Mha-m)**	**No of Years Required**
1	0.65	100	-	1.066×10^{10}	0.0010	0.1	100.00
2	0.55	100	100	6.8×10^{10}	0.0060	0.1	16.67
3	0.45	100	100	2.13×10^{11}	0.1940	0.1	5.16
4	0.35	100	100	7.107×10^{11}	0.0650	0.1	1.55
5	0.25	100	100	1.244×10^{12}	0.1131	0.1	0.88
6	0.15	100	100	1.031×10^{12}	0.0937	0.1	1.06
7	0.05	100	100	2.594×10^{11}	0.0236	0.1	4.24
8	0.00	100	100	1.638×10^{10}	0.0015	0.1	67.16
Total							196.72

DISCUSSION

The result of the above analysis shows that the 600MW full capacity cannot be realized in the month of April since the initial and the final storages were negative. Until the month of September when the final storage became positive which shows high inflow into the reservoir. Also the month of October, November and December final storage also shows negative this indicates that the flow cannot run full plant capacity throughout the year, so the output power was then reduced by removing the equivalent of one turbine of power (i.e. 150MW). The same process was repeated with the total output power of 450MW, then for this output power both the initial and the final storage throughout the year came out positive. This shows that the flow has a firm (primary) power of 450MW and that an additional flow is needed to achieve the full plant capacity of 600MW (Table 3).

From the mean monthly inflow it was observed that the minimum inflow was 2,945 MCM in the month of April and a maximum of 8,623MCM in the month of September. From the analysis, it shows that the reservoir has never had a firm power output of 600 MW in any year.

The analysis also shows that the high evaporation rate adversely affects the storage capacity, with the reservoir having a maximum evaporation rate of 1,439 MCM in January.

Estimation of Shiroro Useful Life

Shiroro Reservoir useful life was estimated to be 196.72 years based on the average annual sediment inflow of Kaduna River. However, useful life ought to be computed with all the annual sediment inflow. Since there are inflows of less than 30 percent of other river, it shows that reservoir useful life should be less than 196.72 years if the sediment inflow of the tributaries were obtained. Therefore calculating for 100% inflow, the useful life is 137.7 years (1984 to 2122). This means that by the year 2122 the reservoir cannot accommodate inflow because it will be filled up with sediments.

Estimation of Seepage of the Shiroro Reservoir

From the analysis, the seepage through the dam was estimated to be 725.19 m^3/day and the volume of water that seeps each month was computed by multiplying the seepage value obtained by the number of days in the month. This shows that insignificant quantity of water is loss through seepage. However, the accuracy of this analysis is subject to the limitation of the Darcy's law.

CONCLUSION

The conclusions drawn from the analyzed are:

i. From the water budget analysis, it was observed that the plant cannot operate at optimum capacity throughout the year due to low inflow, especially in the month of April. Therefore, additional inflow is needed to cater for the low inflow. The additional inflow needed was estimated to be 204.5m^3/s
ii. The reservoir can only operate three turbines (i.e. 450MW) throughout the year.
iii. From the analysis, the seepage through the Dam was estimated to be 725.19 m^3/day.
iv. The useful life of the reservoir was obtained to be 125.32years.

Recommendations

Because of the key role the Shiroro hydroelectric power plant plays in our country today (supply of electric power to Abuja, the federal capital territory and other neighboring states), it is important to harness all available opportunities to make the plant function in full capacity for all periods of the year. Recommendations on how to improve the operations of the plant among others are as follows:

i. Water recycling should be carried out either by pondage or pumped storage to balance the low inflow during the month of April. Pumping could suitably be carried out for some hours during low power demand periods like in the night and at weekends.
ii. Apart from the Kaduna River, the sediment load of contributing rivers as part of the inflow should also be estimated to improve the validity of this research work.
iii. Debris basins or sediment retention basins should be constructed on the feeding rivers especially Kaduna River, so as to trap and localize sediments. This will encourage less cost dredging as the need arises.

REFERENCES

Adie, D.B., Ismail, A., Otun, J.A. and Ajibike, M.A. (2008). Hydrological Analysis and Re-use of Kainji-Jebba Hydroelectricity tail Water. *The Zaria Geographer*, **17(1):** 38-43

Adeogun, B.K. (2008). Analysis of Sedimentation in Kubanni Reservoir, M.Sc. Thesis, Department of

Water Resources and Environmental Engineering, Ahmadu Bello University Zaria, Nigeria (Unpublished).

Dandenkar, M.M. and Sharma, K.N. (1979). *Water Power Engineering*. Vikas Publishing House PVT Ltd, New Delhi.

Modi P.N and Seth S.M (1991). *Hydraulics and Fluid Mechanics*. Standard Book House, Delhi, India. Pp 1149.

MRT Consulting Engineers (1979). Water Supply Master Plan (Vol. 1 Water Resources). Kaduna State Water Board.

NEPA (1984). Completion of Shiroro Dam Final Report, National Electric Power Authority, Nigeria.

Nwugiofor, O.J. (2006). Determination of the tread of water table at the Chanchaga Irrigation Scheme, Niger State. B.Eng. Dissertation, Federal University of Technology, Minna, Nigeria (Unpublished).

Sanyu and Sunmiko Consultants (1995). The Study of the National Water Resources Master plan. Japan International Cooperation Agency and Federal Ministry of Water Resources and Rural Development, Nigeria.

Linsley R.K. and Kohler, J.L. (1992). *Hydrology for Engineers*, McGraw Hill, New York.

U.S. Corps of Engineers (1989a). Reservoir Sedimentation (Em 1110-2-400; Ch 5) www.usace.army.mil

U.S. Corps of Engineers (1989b). Trap Efficiency of Reservoir (Em 1110-2-400; App. F) www.usace.army.mil

U.S. Corps of Engineers (1995). Sediment Measurement Technique (Em 1110-2-400; Ch 8) www.usace.army.mil