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Combining Rippls' Mass Curve and Loucks Sequent Peak Procedure to Determine Reservoir Capacity: The Case Study of Owena River in Ondo State, Nigeria

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Abstract: The yield and the reservoir capacity of River Owena in Ondo State were estimated using a combination of the Rippl's mass curve and the Loucks Sequent Peak Procedure. The yield was found to be $299.99\times10^6 m^3$. However, the reservoir capacity obtained from the mass curve was $125\times10^6 m^3$. This is lower than the yield value and if used for the dam design, there will be a danger of the reservoir capacity not being able to meet the expected demand. Further analysis was done using the Loucks Sequent Peak Procedure. The value from this procedure was $3.30\times10^9 m^3$. This capacity is safe and reliable and will ultimately meet the water demand of the people in the coverage area.

Key words: Mass curve, yield, reservoir capacity, water demand, sequent peak

INTRODUCTION

A dam is a barrier constructed across a natural waterway (river, stream etc.) to create a storage, which is generally called a lake or a reservoir. The purpose of a dam according to Chow *et al.* (1988) is to create storage of the water coming from upstream and optimize its discharge according to the various needs downstream for domestic, industrial and irrigation uses, as well for environmental protection.

Building of dams for impounding water has been practiced for at least 6,000 years but it is largely during the present century that it has gained recognition as an important tool for the development of water resources. In general, a yearly regulation of the storage is obtained and the rainy season provides an excess of water to be stored in the reservoir and used later during the dry season.

When considering storage or impoundment of water in a reservoir, a careful study of the capacity of the reservoir becomes necessary. The capacity of a dam is defined as the volume of water capable of being impounded at the top of the dam. The capacity of a dam should not be too small to meet the demand or it should not be extravagantly large so that its capacity is never or rarely utilized (Khan and Enayetur, 2004). Hence, the proper capacity of dam is necessary for maximum benefit.

Systematic investigation for determining the capacity of a dam dates back from the work of Rippl (1883). Rippl determined the capacity of a dam by the mass curve method.

This method is based solely on the historical inflow record. Since then, many workers have developed theories on determination of the capacity of dams. For example, Moran (1954) formulated the probability theory of storage systems, which has now been developed into an active branch of applied probability. Gould (1961) suggested Moran-type model to account for both seasonally and serial correlation of inflows to determine the capacity. McMahon (1976) took 156 Australian rivers and used Gould's modified procedure to estimate the theoretical storage capacities for four draft conditions (90, 70, 50 and 30% of mean annual flow) and three probabilities of failure values viz: 2.5, 5 and 10%).

Langbein (1958) gave probability routing method to determine the capacity with correlated annual flow. Hardison (1965) generalized Langbein's probability routing procedure using theoretical distributions of annual flows and assuming serial correlation to be zero. He determined capacity graphically for a given chance of deficiency and variability. The annual storage estimates were shown graphically for Log-Normal, Normal and Weibull distributions of annual flows.

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Melentijevich (1966) obtained expressions for both time dependent and steady state distributions of reservoir content assuming an infinite storage and independent normal inflows. In considering finite reservoirs, Melentijevich used a random walk model and a behaviour analysis of 100,000 normally distributed random numbers. From the analysis, he obtained an expression for the density function of the stationary distribution of storage contents.

In the studies conducted on Mitta River of Australia using 34 years of historical record to determine the dam capacity, Khan in association with Enayetur (2004) found that first order autoregressive log-normal distribution was the best fit for the inflow records and hence, annual Markov model was appropriately used.

Among other important techniques, sequent Peak Algorithm, Alexander's method, Dincer's method etc. (McMahon and Mein, 1978) are important.

Wanielista (1990) adopted the Ripple's Mass Curve method in the determination of the yield and reservoir capacity. This method is also favoured by Dandella and Sharma (1979). According to Wanielista (1990) a mass curve is a deterministic model using the volume and yield of a proposed reservoir site. For each time sequence the cumulative input volume are plotted against time. The volumes are cumulated from available streamflows.

The difference between any two points on the cumulative volume curve is a storage volume for that period of time. The yield is the rate of demand for water; it is represented as a constant value for direct supply mode of operation.

In view of the limited data available for this study, direct mode of operation was adopted with the Rippl's Mass Curve method favoured for the estimation of the yield of the reservoir and Loucks *et al*. (1981). Sequent Peak Procedure adopted for the determination of the storage capacity.

STATISTICAL ANALYSIS OF THE RESERVOIR CAPACITY

Rippl's mass curve technique used for this study is a deterministic model using the volume and yield of the proposed Owena reservoir site.

For each time sequence, the cumulative input volume was plotted against time. According to Wanielista (1990) the cumulative volume is expressed as a function of streamflow as

$$\text{Volume} = \int Q dt = \sum Q(\Delta t) \tag{1}$$

Where, Q is the inflow volume and Δt time difference between each record taken.

If the reservoir specific release (demand) at any time t is R_t and d_t represent the positive or negative difference between the inflow and the reservoir release.

$(R_t\text{-}Q_t)$, then maximum positive cumulative difference D_t between the releases and inflows in period t and extending up to period T is

$$D_t = \underset{1 \leq j \leq T}{\text{maximum}} \left(\sum_{t}^{j} d_t\right) \tag{2}$$

The required active storage capacity K_a is the maximum of the maximum cumulative difference D_t

$$K_a = \underset{1 \leq j \leq T}{\text{maximum}} (D_t) \tag{3}$$

Combining Eq. 2 and 3, the active storage requirement is j

$$K_a = \underset{1 \leq i \leq j \leq T}{\text{maximum}} \left[\sum_{t=1} (R_t\text{-}Q_t)\right] \tag{4}$$

If the releases (yield) outstrip the reservoir capacity, the reservoir will not be able to meet the demand. In this case, a sequent Peak procedure proposed by Loucks *et al*. (1981) was used to obtain a new active storage capacity for the reservoir.

According to Loucks, Let K_t be the storage capacity required at the beginning of period t, R_t be the required release in period t and Q_t be the inflow. Setting K_o equal to 0, the procedure involves calculating K_t using the equation

$$K_t = \{R_t\text{-}\ Q_t\text{+}R_{t\text{-}1}\} \text{ if positive, otherwise, } 0 \tag{5}$$

The maximum of all K_t is the required storage capacity for the specified releases.

The combination of the Rippl's and Louck's technique was therefore adopted for the determination of the yield and reservoir capacity of River Owena.

Estimation of water demand: To determine the water demand of any community, it is very necessary to know the population. An underestimation could render the engineering works inadequate very quickly thereby making designing, reconstruction and refinancing necessary (Oyegoke and Oyesina, 1984). On the other hand, a gross overestimation could lead to excessive capacity that must be financed by a smaller population at a considerably high unit cost (Steel and Mcahee, 1979).

Consequently in this study, the population of the community that could be better served by the available water based on the determined yield of the dam has been estimated.

Method of population forecast: Most population forecasting methods require the knowledge of the past and present population concerned. These methods employ the initial population as a base for projecting into the future. According to Oyegoke and Oyesina (1984) these methods operate best where there has been reliable and consistent collection of data on population. Broadly speaking, methods of population forecasting according to Oyegoke and Oyesina (1984) include the graphical method, the ratio methods, the mathematical methods and the component methods.

Of the methods, the mathematical methods are commonly used. The use of mathematical equations for population forecasting assumes that past population growth has followed some identifiable mathematical relationships in which population was a function of time and that future changes will follow a pattern predictable from the relationship. The two similar models commonly applied are: The geometric model and the exponential model (Oyegoke and Oyesina, 1984).

Constant rate functions are used in these models to derive the size of the population at some past or future date provided essential parameters are given such as: Size of population at a defined point in-time (initial population); growth rate per unit time and the length of the interval for which projection are made.

According to Oyegoke and Oyesina (1984) the models are expressed as

$$P_{(t+n)} = P_t(1+r)^n \text{ (Geometric growth model)} \tag{6}$$

$$P_{(t+n)} = P_t\, e^{rn} \text{ (Exponential growth model)} \tag{7}$$

Where,

$P_{(t+n)}$ = The population at time (t+n), a future date.

P_t = Population at present time t.

r = The rate of growth per unit time.

n = The length of time for which population is made.

In Nigeria, the population based on a growth rate of 2.83 is assumed (NPC, 1991). For the purpose of this study, the geometric growth model is favoured in the estimation of the population of the community that will be served by the expected dam capacity.

Water requirements: Water use and consumption data are frequently expressed in litres per capita (head) per day. Estimating the average daily per capital consumption, is usually done by extrapolating from tables of consumptions of other areas. A different approach is to estimate by considering factors that affect water consumption in that particular community. White combined several factors that affect domestic water consumption in their study in East Africa and obtained a relationship between domestic per capita consumption and type of housing density. In another study, by Areola and Akintola in Ibadan, Nigeria, the basic per capita consumption for planned residential areas was found to be 89 L per capita. Ondo State Water Corporation adopted the per capita consumption of 120 L for urban residential areas like Akure (ODSWC, 1999). This demand is favoured in the estimation of the full water demand for the study area.

MATERIALS AND METHODS

Discharge records of River Owena taken from the gauging station located along Ilesha-Ibadan expressroad at Owena village in Ondo State, Nigeria, was collected from the Ondo State Water Corporation and used for this study.

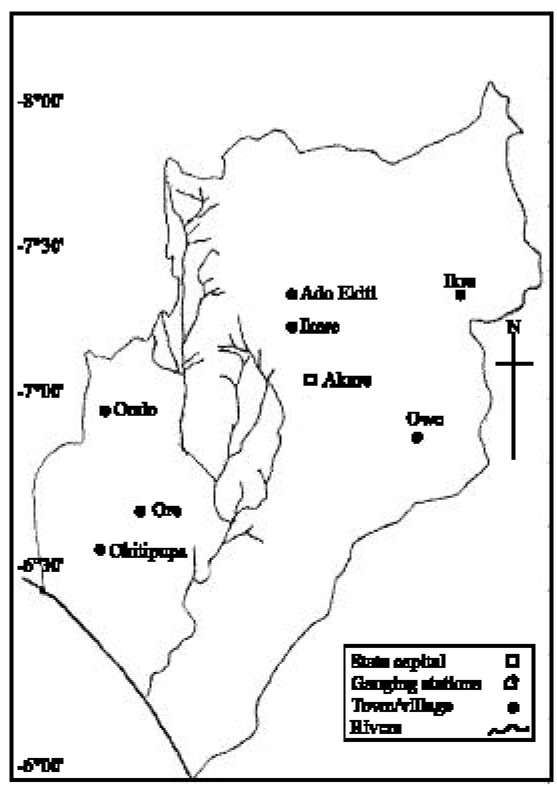

Fig. 1: Location of River Owena, its tributaries and gauging stations

Appendix 1: Monthly discharge records of River Owena in $m^3 s^{-1}$ (1993-2002)

Year	Jan	Feb	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1993	0.95	1.20	1.600	1.500	2.600	7.025	9.461	10.451	15.545	14.032	3.059	1.537	68.960
1994	1.014	0.915	0.652	1.539	2.736	5.686	9.136	20.230	23.210	13.060	3.010	1.610	82.800
1995	0.981	1.51	1.323	1.687	7.263	6.080	43.984	41.239	30.330	13.648	4.253	3.394	155.690
1996	2.14	1.50	1.365	2.341	3.736	7.213	10.500	12.606	45.795	15.533	7.643	3.601	113.970
1997	1.65	1.21	1.010	1.690	2.680	2.890	3.904	3.602	16.957	21.330	5.198	2.205	64.330
1998	1.207	0.996	0.934	0.855	1.188	1.968	5.512	6.248	5.218	33.225	20.458	5.230	83.040
1999	1.531	0.852	0.800	0.732	1.610	2.531	6.341	6.432	30.432	35.021	25.331	11.120	122.730
2000	8.32	4.025	2.451	2.551	3.461	6.300	5.421	38.211	42.231	20.003	12.241	4.621	163.290
2001	0.879	0.725	0.700	1.253	3.120	12.570	14.331	33.421	35.337	30.210	10.303	3.225	146.070
2002	1.21	1.00	0.940	0.890	2.730	4.730	10.620	24.770	28.770	31.930	25.210	11.010	143.810
Total	19.90	13.933	11.775	15.038	31.124	56.990	129.21	197.21	173.83	227.990	116.706	47.544	
Average	1.99	1.390	1.180	1.500	3.110	5.700	12.920	19.720	27.380	22.800	11.670	4.750	

River Owena is perhaps the most popular river in Ondo State. It flows within an area bounded by Longitude 5° 01` E and Latitude 7° 17` North of the Equator and Longitude 5° 45` E and Latitude 8° 15` North in South Western Nigeria. The drainage area of Owena River is 790 km^2 (BORBDA, 1991). The river has its source in the hills in the Northwest of the catchment area around Effon Alaaye in Ekiti State and flows directly Southwards to be joined by the Ofosu and Aden Rivers north of the Siluko Village in Ondo State and then, as the Siluko River, flows into the estuarine creek area. Figure 1 shows the tributaries and the location of the gauging stations on River Owena.

The ten- years (1993-2002) monthly discharges of the river so obtained is shown in Appendix 1. Then, the Rippl's mass curve technique was used to analyze the yield and the reservoir capacity of the river. The technique entails the following: Firstly, all the discharges in $m^3 sec^{-1}$ that occurred in January of each year of the ten years were added together and the mean found. Similar procedure was applied to all the other months of the year. Secondly, ten percent of the mean monthly discharges was assumed as losses due to evaporation, seepage etc. (Serge, 1960). The remaining 90% mean monthly discharges were converted to volume by multiplying them (discharges) by the number of seconds in each month for the 10-year period. Thereafter, these volumes (m^3) were then cumulated month by month, that is, the volumes for January in each year for the ten years were cumulated and the same approach was applied to all the other months. The highest value among the cumulative volumes obtained was taken to represent the safe yield of River Owena.

The Rippl's mass curve was obtained by plotting the cumulative volumes against the corresponding months. The yield line was then scaled and drawn across the cumulative inflow volume curve. The maximum vertical distance between the cumulative inflow volume curve and the release line was found and this represented the active storage capacity of the reservoir (Serge, 1960).

However, the value of the reservoir capacity obtained was found to be smaller than the yield of the reservoir: An indication that the reservoir will not be able to meet the demand, hence further analysis using the Loucks Sequent Peak Procedure given by Eq. 5. The procedure was used to derive a new capacity that will be safe and reliable for the river. The procedure stems from the Rippl's mass curve technique, which assumes constant water releases or draft from the reservoir.

Loucks Sequent Peak Procedure requires that, for each month, the inflow volume be deducted from the release or yield and the result added to the previous reservoir capacity to obtain the current required capacity of the reservoir.

Water requirements: The populations of the coverage areas were collected from the National Population Commission, Akure, Ondo State, Nigeria based on the 1991 Census. There were five local governments in the coverage area. The current populations of the areas were computed using equation 6 based on the growth rate of 2.83 (NPC, 1991). This is shown as Appendix 1.

RESULTS AND DISCUSSION

In estimating the water yield and the reservoir capacity of River Owena, the monthly discharges of the river were obtained as shown in Appendix 2. The Rippl's mass curve technique was used to obtain the yield of the river. The result is shown in Table 1. As it can be seen in the table, the discharges that occurred in January of each year of the ten years were added together and the mean found. Similar procedure was applied to all the other months of the year. The actual mean flow is shown in column 2.

Ten percent of the mean monthly discharges was assumed as losses due to evaporation, seepage etc. according to Serge (1960). The remaining 90% of the mean monthly discharges are shown as net inflow in column 3.

These net flows were converted to volume by multiplying them (discharges) by the number of days, hours, minutes and seconds in each month for the ten-year period as shown in column 4.

Table 1: Estimation of water yield of Owena River using rippl's technique

Month	Actual mean flow (m^3 s^{-1})	Net flow (m^3 s^{-1})	Volume (m^3)×10^6	Cum.volume (m^3)×10^6
January	1.99	1.791	4.79	4.79
February	1.39	1.251	3.03	7.82
March	1.18	1.062	2.84	10.66
April	1.50	1.35	3.50	14.16
May	3.11	2.799	7.50	21.66
June	5.70	5.13	13.3	34.96
July	12.92	11.628	31.14	66.10
August	19.72	17.748	47.54	113.64
September	27.38	24.642	63.87	177.51
October	22.80	20.52	54.96	232.47
November	11.67	21.633	56.07	288.54
December	4.75	4.275	11.45	299.99

Table 2: Estimation of reservoir capacity of River Owena using Loucks sequent peak procedure

Period t 1	Release R_t×10^6(m^3) 2	Inflow Q_t×10^6(m^3) 3	Previous required capacity K_{t-1}×10^6(m^3) 4	Current required capacity K_t×10^6(m^3) 5
January	299.99	4.79	0	295.20
February	299.99	3.03	295.20	592.16
March	299.99	2.84	592.16	889.31
April	299.99	3.50	889.31	1185.80
May	299.99	7.50	1185.80	1478.29
June	299.99	13.30	1478.29	1764.98
July	299.99	31.14	1764.98	2033.83
August	299.99	47.54	2033.83	2286.28
September	299.99	63.87	2286.28	2522.40
October	299.99	54.96	2522.40	2767.43
November	299.99	56.07	2767.43	3011.35
December	299.99	11.45	3011.35	3299.89

Thereafter, these volumes (m^3) were then cumulated month by month, that is, the volumes for January in each year for the ten years were cumulated and the same approach was applied to all the other months. The cumulated result is as shown in column 5. The highest volume of the cumulative volumes obtained, that is, 299.99×10^6 m^3 was taken to represent the safe yield of River Owena.

The Rippl's mass curve was therefore obtained by plotting the cumulative volume against their corresponding months as shown in Fig. 2. The vertical ordinate drawn between the mass curve and the yield line as shown in the figure gave the storage capacity. The value of the reservoir capacity obtained from the mass curve was 125×10^6 m^3. This value was found to be smaller than the yield of the reservoir; which clearly showed that the capacity would not be able to cope with the expected demand. Therefore, Loucks Sequent Peak Procedure (Loucks *et al*., 1981) was then used to obtain a new capacity for the reservoir.

The procedure stems from the Rippl's mass curve technique, which assumes constant water releases or draft of 299.99×10^6 m^3 from the reservoir. The result of the analysis is shown in Table 2.

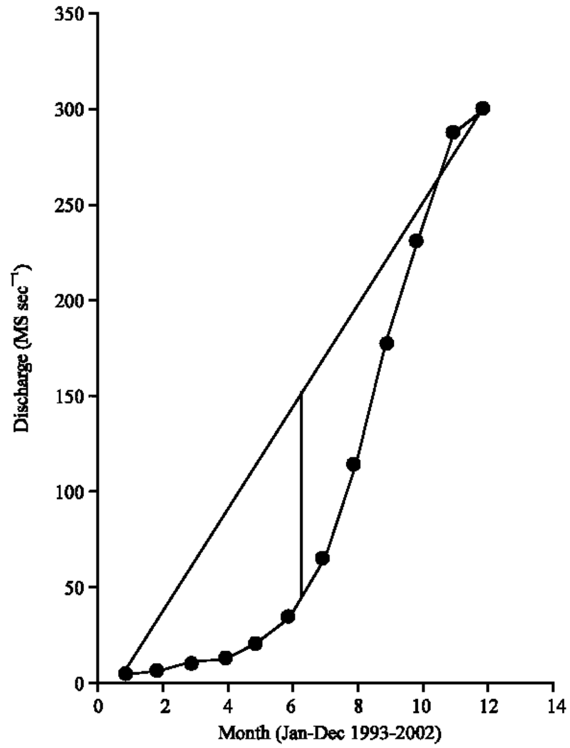

Fig. 2: Mass curve for determination of reservoir capacity

From Table 2, column 1 shows the months of the water year, which begins in January. The constant water releases or draft from the reservoir as obtained from the Rippl's mass curve analysis is shown in column 2. Column 3 shows the net inflow volume as computed also from the Rippl's mass curve analysis. For each month, the inflow volume was deducted from the release and the result added to the previous reservoir capacity in column 4 to obtain the current required capacity of the reservoir as shown in column 5. That is, for January, the inflow volume (4.79×10^6 m^3) was subtracted from the release (299.99×10^6 m^3). The reservoir was initially assumed to be empty, that is, the previous reservoir capacity was taken as zero for January. The inflow volume of 4.79×10^6 m^3 was subtracted from the release (299.99×$10^6$$m^3$) to obtain the current required reservoir capacity of 295.20×10^6 m^3 for January. For February, the net inflow volume of 3.03×10^6 m^3 was subtracted from the release. The result was added to the capacity of the reservoir for January to obtain 592.16×10^6 m^3, which represented the current required capacity of the reservoir for February.

This procedure was followed for subsequent months and the capacity of the reservoir for other months in the year were found as shown in column 5.

The highest value of all the current reservoir capacities of the twelve months was 3.30×10^9 m^3. This value represented the required safe reservoir capacity of River Owena.

Appendix 2: Population of the coverage areas projected to year 2007

Local government	1991 Census	Projected population upto 2007
Akure	316,925	495,306
Ondo	247,214	386,358
Ifedore	102,138	159,626
Ileoluji/Okeigbo	123,397	192,851
Owena/Idanre	81,654	127,613
Total	871,328	1,361,754

As can be seen from the Table 2 therefore, the Loucks Sequent method provides a better way of operating the reservoir month by month, apart from showing the safe capacity of the reservoir. The rate of withdrawal is obviously lower than the capacity of the reservoir in any month. This makes the reservoir safe and reliable.

The method also provides a better way of regulating the diversity of uses to which the water from the reservoir may be put.

Going by 1991 census, the population of the coverage area of Owena River was 871,328 (Appendix 1). Using a growth rate of 2.38 (NPC, 1991), the current population is 1,361,754. With a consumption rate of 120l/c/d (ODSWC, 1999), the water demand of the people per day will be 1.63×10^{8}litres or $1.63\times10^{5}m^{3}$. This is obviously lower than the capacity, of the reservoir, (3.3×10^{9} m^{3}). The water is therefore, not only adequate for municipal water supply but also could serve the purpose of irrigation and hydroelectric power generation.

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