TRAINING COURSE

ON

RESERVOIR OPERATION

(UNDER WORLD BANK AIDED HYDROLOGY PROJECT)

Module 3

Storage - Yield Analysis

BY

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STORAGE-YIELD ANALYSIS

1.0 INTRODUCTION

Having estimated the water requirements for an intended project and having assessed the available water resources at a prospective site, a planning engineer is faced with one of the three situations:

a. The rate at which resources are available is always in excess of the requirements.
b. The total available resources over a time period is equal to or in excess of the overall requirements, but the rate of requirement at times exceeds available rate.
c. The total available resources are less than the overall requirements.

In first case, water can be used directly from the stream as and when needed. A storage reservoir is the solution to the second case. In third case, a supplemental source or an alternative site has to be explored. Once it is certain that the total available resource is more than requirements and a particular site for storage reservoir is finalized, the next important decision to be taken is about the capacity of the reservoir to be constructed.

The procedures for estimating storage capacity needed to meet the given demands or the possible yield from a given project configuration and flow data constitute the storage-yield analysis. This discussion will concentrate mainly on the methods of computing capacity for a reservoir.

2.0 DATA REQUIREMENTS

Following data are, in general, needed for determination of required storage capacity of a reservoir:

a) Runoff Data

Sufficiently long runoff data series at the site of reservoir must be available. If this series is not available from the past records, the same can be developed using precipitation data or using the data at nearby sites.

b) Elevation-Area-Capacity Table

This is constructed by measuring area enclosed between two contours and then multiplying the average area by the contour interval. The map used should be an accurate one and the contour interval should be sufficiently small.

c) Evaporation Data at the Site

If it is not available, data for a nearby site which is hydrometeorologically similar to the proposed site may be considered. Sometimes evaporation losses are neglected in the preliminary computations.

d) Time Series of Target Demands from the Reservoir

Target demands may be computed by using projected population and water use per capita.

e) Required Reliability

By default, 75% dependability is assumed for irrigation, 90% for hydroelectric power and 100% for water supply. These norms are specified by Government of India.

f) Rate of Sediment Inflow into the Reservoir

g) Height vs Cost of the Construction of Dam

3.0 DETERMINATION OF RESERVOIR STORAGE CAPACITY

The storage capacity of a reservoir is divided into a number of zones based on the useful purposes, a reservoir is required to serve. Here we take step by step, each zone and the criteria for fixing size for that zone.

3.1 Dead Storage Capacity

Dead storage is provided in a reservoir to serve two purposes:

a) The river, during its course to the reservoir, picks up sizeable amount of sediment and carries it along either as suspended load or bed load. Upon entering a reservoir, the velocity of flow becomes virtually zero and hence its carrying capacity is lost. So the sediment settles down and it keeps on accumulating as the time passes on. On account of this accumulation, the effective storage capacity of the reservoir and hence its reliability goes on reducing with time.

b) Many times, the water released from the reservoir is passed through the turbines of power plants located downstream of the dam to generate hydroelectric power. For efficient working of turbines, it is necessary that head variation must be within a specified range and a minimum head must always be available.

These two considerations necessitate the provision of dead storage in the reservoir. To compute the amount of sediment inflow expected in the reservoir, average sediment yield of the catchment is determined. This is then used to compute total sediment load expected during the economic life of the project. The storage actually provided is covered by the greater of the two factors discussed above.

3.2 Flood Control Storage Capacity

The requirement of storage for flood control is in conflict with the requirements for conservation needs. The conservation requirement, like water supply and hydropower generation require the storage space to be full while the flood control aspect requires the availability of empty storage space.

From the point of view of analysis, the demands for water supply and hydroelectric power are relatively deterministic in nature while the demand for flood control storage is completely stochastic. Further, the time period for analysis is usually of the order of one month for the conservation purposes while for flood control purposes, it is of the order of few hours. The storage requirement can be estimated by using the design flood hydrograph. An initial reservoir level is assumed at which this flood hydrograph impinges the reservoir. The maximum level attained by the reservoir is computed by routing the hydrograph through the reservoir. The maximum height of the dam is obtained after adding the free board to this level. To begin with, top of conservation pool is a good choice for initial storage for computations. But in case it is required to have the reservoir full after the flood season is over, the water level in the reservoir is likely to be above the conservation pool in the later part of flood season and choice of a higher initial storage for computation will be more appropriate.

3.3 Storage Requirement for Conservation Purposes

A number of techniques are available for computing storage capacity for conservation purposes like irrigation, municipal and industrial water supply, hydropower generation etc. Depending upon the type of data and the computational technique used, the popularly used reservoir capacity computation procedures are classified into following categories:

a) Critical period techniques
b) Optimization techniques
c) Simulation techniques

Among these techniques, those based upon critical period concepts are the earliest techniques. One such method, known as the *Mass Curve Method* was the first rational method proposed to compute the required storage capacity of a reservoir. With the advent of computer, the techniques, which beneficially use its computational capabilities are increasingly being used. Among the optimization techniques, those based on Linear Programming (LP) have been found to be particularly suitable. The third method is simulation which can also be used to further modify and test the results of first two methods.

3.3.1 The Mass Curve Method

Also known as Rippl mass curve method, it is a simplified method commonly used in planning stage. The method considers the most critical period of recorded flow. The critical period is defined as the duration in which initially full reservoir depletes and passing through various states empties without spilling. In the methods based on critical period concept, a sequence of streamflows containing a critical period is routed through an initially full reservoir in presence of specified demands. The reservoir capacity is obtained by finding the maximum difference between cumulative inflows and cumulative releases. Let us define a function X(t) as:

$$X(t) = {}_{t}\int x(t)\,dt \qquad \ldots(1)$$

then the graph of X(t) versus time is known as the mass curve. The mass curve technique, proposed by Rippl in 1883 to determine storage capacity of a reservoir, is a graphical technique.

Equation can be solved either graphically or analytically. In the graphical method, mass inflow curve and mass yield curve accumulated separately. Yield represents the total demand for water and evaporation. For a constant draft rate, the yield curve is a straight line having a slope equal to the draft rate. At each high point on the mass inflow curve, a line is drawn parallel to the yield curve and extended until it meets the inflow curve. The maximum vertical distance between the parallel yield line and the mass inflow curve represents the required storage. Assuming the reservoir is full at A as in Fig. 1, going from A to E along the mass curve represents the same volume of water as going from A to E along the straight line.

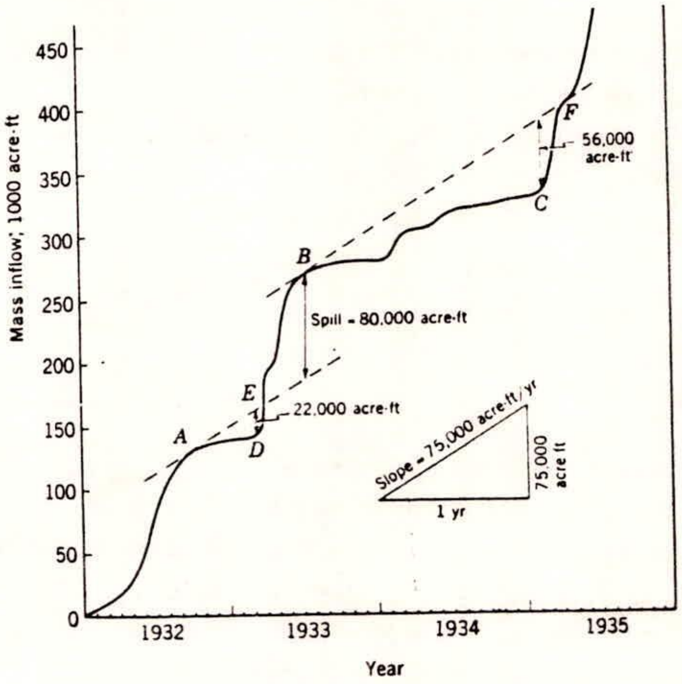

Fig. 1 Mass Curve for Storage Analysis

The mass curve technique, although very simple and straight forward, has few shortcomings. One drawback is the implicit assumption that the storage which would have been adequate in past will also be adequate in future. Although this is not clearly true, the error caused is not really serious particularly if sufficiently long flow series has been considered. However, this problem will arise in any other method since true future is not known. Some methods try to address this problem by explicitly considering the stochasticity of the inflows. One more drawback of the mass curve is that explicit economic analysis can not be done in this technique. The storage size can not be related to the economic life of the project. Further, it can not be computed for a particular level of reliability.

A similar method was a introduced in Europe and was known as '*The Stretched - Thread Rule*'. Let x be the series of inflows to the reservoir and q be the outflow or draft series and Z be defined as

...(2)

$$Z_t = {}_0\int^t (x-q)\, d\tau$$

or

$$Z_t = {}_0\int^t x\, d\tau - {}_0\int^t q\, d\tau = X_t - Q_t$$

The plot of Z_t with respect to time represents storage fluctuations in an unconstrained reservoir subject to inflow x and outflow q. This graph can be used to find the smallest size of the reservoir required to supply draft series throughout the critical period without failure. Here it is assumed that the reservoir does not spill during the critical period or it is a topless reservoir. Many times, it is more convenient to express release as a ratio of mean inflow and this ratio is called the degree of regulation. Similarly, the storage capacity can also be expressed as a ratio of mean annual inflow and is called storage ratio or storage coefficient.

3.3.2 Sequent Peak Algorithm

Analytical solution of mass curve method is given in Sequent peak algorithm. It is particularly suited for the analysis of large data with the help of a computer. This method was proposed as a method which circumvents the need to choose the correct starting storage which is required in the mass curve procedure. The computations are quite simple and can be carried out as follows. Let I_t be the inflow to the reservoir in the period t, R_t be the release from the reservoir, and S_t the storage at the beginning of the period t. The reservoir is assumed to be empty in the beginning. The mass curve of cumulative net flow volume (Inflow - Outflow) against chronological time is used. This curve, shown typically in Fig.2, will have peaks (local maximums) and troughs (local minimums). For any peak P_i the next following peak of magnitude greater than P_i is called a sequent peak. The computations are performed for twice the length of the inflow record. It is assumed that the inflows repeat after the end of first cycle. This assumption is made to take care of the case when the critical period falls at the end of the record. The variable S_t is calculated by the following equation:

...(3)

$$S_t = \begin{cases} S_{t-1} + R_t - I_t & \text{if positive} \\ 0 & \text{if negative or zero} \end{cases}$$

The required storage capacity is equal to the maximum of S_t values. The computations are illustrated in the following table for a simple case where it is required to release 5 units of water from the reservoir and the inflows are as given in column 4 of the following table.

Thus the required reservoir capacity would be 12 units which is the maximum of the last column in the above table. Here the calculations are not repeated for the second cycle because the storage at the end of first cycle is zero and therefore the second cycle would be identical to first cycle.

Period	Storage required in previous period	Release	Inflow	Storage needed in the present period
t	$[S_{t-1}$ +	R_t -	$I_t]$ =	S_t
1	0	5	3	0
2	0	5	4	1
3	1	5	4	2
4	2	5	1	6
5	6	5	2	9
6	9	5	2	12
7	12	5	6	11
8	11	5	5	11
9	11	5	8	8
10	8	5	9	4
11	4	5	7	2
12	2	5	7	0

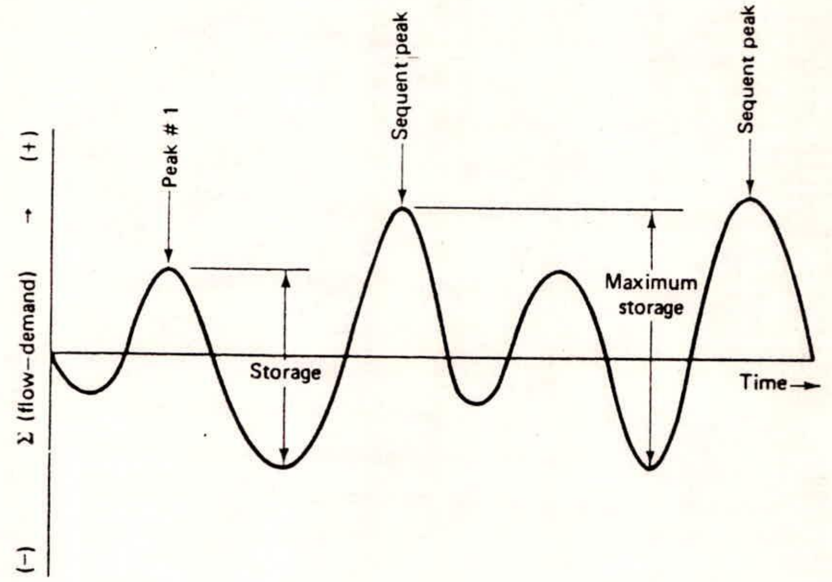

Fig. 2 Definition Sketch for Sequent Peak Algorithm

The sequent peak algorithm can very easily consider the variable release from the reservoir. The reliability of the reservoir can be obtained indirectly. Since the reservoir would be able to meet the worst drought from the record, the implied probability of failure would be 1/(N+1). The algorithm is very fast and easy to program. A single historical record is used to compute the storage and hence the method is limited in that sense. It is also not possible to exactly consider the losses, these can be approximately included in the releases.

3.3.3 Storage-Yield Analysis

Storage yield analysis is used to determine the volume of reservoir storage required to augment river flow in order to provide a specified water demand with a stated reliability. It is also used to reassess the water demand which can be satisfied by existing reservoirs. Storage volume depends upon the volume of demand D, specified reliability R and the hydrograph of the catchment supplying the reservoir. Reliability R is an index in the range 0 - 1 which indicates how satisfactorily the reservoir performs. If storage required is to be calculated then yield is known otherwise the storage capacity is known. The Fibonacci search technique is used for the computation of dependent variable, reservoir capacity or annual yield, till desired reliability is achieved with permissible tolerances, supplied by the user.

When a sufficient long record of monthly or annual flows is available, then analysis of that series using suitable methods can provide the required storage capacity estimates once the levels of demand and reliability are specified. The following steps are followed:

a) At the beginning of iteration, the upper bound of the variable is kept equal to the average inflow volume in a year. The lower bound of storage is taken as dead storage S_{min}, whereas for annual yield lower bound is taken as zero.

b) Reservoir is initially assumed to be full.

c) Continuity eqn. is applied for each time unit

$$S_{t+1} = S_t + I_t - E_t - L_t \qquad ...(4)$$

d) The resulting Storage value series can be plotted versus time to show the behavior of the reservoir for the chosen trial capacity.

e) From above results, reliability is calculated.

f) If these values are too small, a large capacity is chosen and steps 1 to 5 are repeated.

g) If reliability values are large, and a smaller value is acceptable, then a smaller capacity is chosen and steps 1 to 5 are repeated.

h) This trial and error is performed till desired value of reliability is achieved.

With the desired accuracy, specified lower bound and calculated upper bound, one dimensional search is carried out to reach the optimum value of variable. The reliability achieved is computed after complete reservoir operation computations, based on mass balance equation. The evaporation loss E_i is function of both S_i and S_{i+1}. Hence an iterative method is applied using elevation-area-capacity table till absolute difference between two successive relative evaporation losses are less than a value supplied by the user. At each time interval, attempt is made to satisfy the demand to the extent possible. If the available water in reservoir is less than S_{min}, no release is made and the storage is depleted by evaporation only and the reservoir is assumed to have failed during that particular month. If during any period, $S_i + I_i \geq C$, the extra water over the storage capacity after meeting the demand is spilled. If there is not enough water in the reservoir to meet the demand any period, the demand is met to the extent possible and the month is treated as failure month.

The reliability achieved (REL) is computed by

$$REL = 1.0 - FAIL/n \qquad \ldots(5)$$

where FAIL = number of failures (number of periods when $R_i < D_i$). The objective function used in Fibonacci search is

$$OF = |REL - RELI| \qquad \ldots(6)$$

where RELI is the reliability desired.

The detail of Fibonacci search method, which is a unidirectional search method for nonlinear optimization problems, can be found in texts such as Rao (1979). The choice of this method over other univariate nonlinear programming techniques is somewhat subjective.

3.4 Optimization Techniques

The advent of computer and the development of optimization techniques has led to the use of both of these to storage-yield analysis. Among the various available optimization techniques, Linear Programming (LP) and Dynamic Programming (DP) are two techniques which have been used extensively. Here, only a LP based formulation is being discussed. The problem formulation is essentially same in case of DP.

Let us consider a situation in which a reservoir is to be constructed at a particular site. Monthly inflow data for past n months is available. The projected demand of water during a critical year is known along with its distributions among each month. The losses from the reservoir are neglected for the time being. The problem is to find out the minimum capacity of reservoir which will supply the required quantity of water without failure. Let X be the annual water demand from the reservoir and α_i, i = 1,2..... 12 be its fractions for different months. Hence the demand in a particular month will be $\alpha_i X$. Let I_i be the inflow to the reservoir during the i^{th} month and R_i be the water actually released from the reservoir.

Representing by S_i, the storage content of the reservoir at the beginning of month i, the continuity equation is:

$$S_i + I_i - R_i = S_{i+1} \qquad \ldots(7)$$

This equation has to be satisfied for each of the n months and hence we shall have n such equations which will be constraints in the formulation. The value of S_i is given as input.

It is also required that the amount of water actually released from the reservoir must be more than or equal to the amount demanded. This can be mathematically expressed as:

$$R_i \geq \alpha_i X \quad i = 1, 2......n \qquad ...(8)$$

Since this condition also must hold for each month, there will be n such constraints. If the capacity of the required reservoir is C, then in any month, from physical point of view, the storage content of the reservoir must be equal to or less than this value. Hence

$$C \geq S_i \quad i = 1, 2......n \qquad ...(9)$$

Moreover, the storage S_i, capacity C and release R_i can take only positive values. This completes the problem formulation. The problem is quite easy to solve particularly due to availability of standard package programs.

3.5 Method of Simulation

Simulation is essentially a search procedure. It is one of the most widely used techniques to solve a large variety of problems associated with the design and operation of a water resources systems. The reason is that this approach can be realistically and conveniently used to examine and evaluate the performance of a set of alternative options available.

Assume that a site has been identified for the construction of a dam. The reservoir has to cater for irrigation for a nearby area and the target demand of water for different months is given. The elevation-area-capacity table for the site is available. A sufficiently long series of streamflows at the site is available. Further, it is required that the reliability of the reservoir should be least 75%. An efficient procedure of binary search can be used to determine the required storage capacity. In this method, first the upper and lower bounds on the capacity of the reservoir are determined. The lower bound can be taken to be zero or the dead storage and the upper bound can be determined from physical factors such as water availability etc. A trial value for the reservoir capacity is selected which is the mean of upper bound and lower bound.

Now, starting with a suitable value of initial storage content, the reservoir is operated using the streamflow data. The effect of this initial storage value will not be very significant if the inflow series for a sufficiently long period, say 30-40 years is being used. During any time period, the release is made equal to the demand if that much water is available in the storage. Otherwise whatever can be made available is released and the reservoir is said to have failed in that period. The evaporation losses can be easily considered if the information about the depth of evaporation is available. In this way, the reservoir is operated for the entire period of record. Now the reliability of the reservoir is computed. If this reliability is less than the desired value, it means that the capacity of the reservoir must be increased. In this case the present capacity is adopted as the lower bound for next iteration. The feasible region below this lower bound is discarded and the trial value for the next iteration is chosen midway the upper bound and new lower bound. If, however, the reliability comes out to be higher than the required limit, the size of the reservoir is bigger than what it should have been and hence the region between the current value and upper bound is discarded for further examination. The present capacity value becomes the new upper bound. Again the trial value for the next iteration is chosen as mean of new upper bound and old lower bound.

The computations are repeatedly performed in this manner and they are terminated when the required convergence is achieved. This method converges quite rapidly as the feasible region is halved every time. It may be seen that in this method, generation of hydroelectric power can also be easily considered.

4.0 IS GUIDELINES FOR FIXING RESERVOIR CAPACITY

The determination of reservoir capacity has been divided in three aspects according to the recommendations of Indian Standard IS: 5477 - 1969. These are being described here.

4.1 Dead Storage

This storage space is provided to cater for the sediment entering into the reservoir along with the streamflow. As the water is sufficiently still in the reservoir, the carrying capacity is lost and the sediment settles down. By earmarking a zone as dead storage, it is ensured that the live storage will work at the full efficiency and also a minimum required head will be available for power plants.

For fixing dead storage, it is very essential to determine sediment yield of the catchment. This can be done by either sedimentation surveys of the reservoir with similar catchment characteristics or by sediment load measurements of the stream. In the first method, the sediment yield is determined by measuring the accumulated sediment in a reservoir for a known period, by using precise measuring devices. The difference between the present reservoir capacity and the capacity just after completion of construction gives the sediment yield. In the second method, suspended load and bed load measurements are taken along with the discharge measurements and the yield is determined using them.

IS: 5477 (part-II) - 1969 recommends following methods for determination of sediment distribution in a reservoir for design purposes:

a) Empirical area reduction method,
b) Area increment method,
c) Moody's method to find new zero elevation.

4.2 Live Storage

Live storage is provided in a reservoir to store excess water during high flows for use during low flows. The live storage is the useful storage between the full reservoir level and the minimum draw down level (in case of power projects) and dead storage (in case of irrigation projects).

According to IS: 5477 (Part-III) - 1969, the following data should be used to fix live storage capacity:

a) Streamflow data for a sufficiently long period,
b) Losses, such as evaporation and seepage and recharge (during the depletion),
c) The contemplated irrigation, power or water supply demand, and
d) Storage- capacity curve at the site.

In case streamflow records are not available at the required site, these at the nearby sites must be used to generate the data for the reservoir site. Similarly, short records must be suitably extended.

Evaporation losses are computed using depth of evaporation multiplied by average water spread area. Unless adequate data are available, no allowance be made for seepage and recharge.

The storage provided for irrigation projects must be able to supply for the demands with 75% dependability; 90% dependability for hydroelectric power and 100% dependability for water supply has been suggested. It has been recommended that mass curve technique should be used to determine required storage capacity.

4.3 Other Considerations

One of the important aspects to be considered in the design of a dam is safety consideration during the extreme floods. The Indian Standards recommend the assumption that the reservoir would be filled to the full reservoir level at the beginning of spillway design flood. This assumption is made to consider improper operation of regulation mechanisms as a result of incorrect flood predictions and mechanical problems in their operation. The methods suggested for estimation of the design flood are broadly classified into:

a) Application of suitable factor of safety to maximum observed flood or maximum historical flood.
b) Empirical flood formulae
c) Envelope curves
d) Frequency Analysis, and
e) Rational method of derivation of design flood from storm studies and application of unit hydrograph principle.

The maximum water level of reservoir is obtained by routing the design flood through the reservoir and spillway. It has been recommended to use continuity equation or Sorensen's Method. Step-by-step method for doing the computations has been discussed in IS: 5477 (Part-IV) - 1971.

The standard also recommends that the following governing factors should be considered while determining the storage capacity of a reservoir.

a) Long - term precipitation records for the catchment
b) Long tern runoff data at or near the reservoir site

c) Sediment yield into the reservoir from the catchment
d) Area and capacity curves

5.0 REFERENCES

McMahon, T.A., and R.G. Mein, Reservoir Capacity and Yield, Elsevier Book Company, Sydney.

Loucks, D.P., J.R. Stedinger, and D.A. Haith, Water Resources Systems Planning and Analysis, Prentice Hall Inc., New Jersey, 1981.

Jain, S.K., Storage Yield Analysis, Report No. UM-16, National Institute of Hydrology, Roorkee, 1987.

Rao, S.S., Optimization, Theory and Practice, Wiley Eastern, 1979.

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