STATE OF ART REPORT

Scientific Contribution
No.: INCOH/SAR-16/97

IMPACT OF SILTATION ON THE USEFUL LIFE OF LARGE RESERVOIRS

R.S. Varshney

INCOH SECRETARIAT
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA
January, 1997

INDIAN NATIONAL COMMITTEE ON HYDROLOGY
(Committee Constituted by Minsitry of Water Resources, Govt. of India)

Scientific Contribution
No.: INCOH/SAR-16/97

IMPACT OF SILTATION ON THE USEFUL LIFE OF LARGE RESERVOIRS

R.S. Varshney
Former Engineer-in-chief
U.P. Irrigation Department

INCOH SECRETARIAT
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA
January, 1997

The presentation of material throughout the publication does not imply the expression of any opinion whatsoever on the part of Indian National Committee on Hydrology (INCOH) or the publishers.

Published by :

Dr. K.K.S. Bhatia
Member Secretary, INCOH &
Scientist F
National Institute of Hydrology
Roorkee - 247 667, India

Printed by :

Ajay Printers & Publishers
19, Civil Lines, (Centenary Gate)
Roorkee - 247 667 (India)
Phone : 01332-73140, 74740
FAX : 01332-74740

PREAMBLE

It has been estimated that the total world population will be about 6.5 billion by the year 2000, with the most rapid growth in the developing countries. By that time, the countries within the humid tropics and the other warm humid regions will represent almost one-third of the total world population. This proportion will continue to rise in the twenty-first century. The developing and under-developed countries thus quite clearly are the regions facing potentially serious water problems. Hence, it is urgent to question as to whether the fields of hydrology and water resources management have the appropriate methods in place to meet the rising demands that will be made on the water resources. Hence it becomes very important and expeditious to review and update the state-of-art in different facets of hydrology and component processes. This calls for compiling and reporting present day technology in assessment of water resources and determining the quality of these water resources.

Soil erosion, its transportation and subsequent deposition in reservoirs is a universal problem. Uncontrolled deforestation, forest-fires, over-grazing, improper methods of tillage, unwise agricultural practices and other man's activities are responsible for accelerated soil erosion. It is estimated that about 6000 Million tonnes of soil is eroded every year in India as a result of sheet erosion. Besides, gully and ravine erosion ravages 8000 ha. annually. During the last 4 decades India has constructed several major/medium river valley projects involving construction of dams and creation of reservoirs for flood controls, irrigation and hydropower. As the above storages are subject to silting, sedimentation of reservoirs is in fact a matter of vital concern to all water resources development projects. Silting not only occurs in the dead storage but also encoraches into the live storage capacity which impairs the intended benefits from the reservoirs. Therefore, the problem of sedimentation needs careful consideration and there is an urgent need to review the status of reservoir sedimentation.

The Indian National Committee on Hydrology is the apex body on hydrology constituted by the Government of India with the responsibility of coordinating the various activities concerning hydrology in the country. The committee is also effectively participating in the activities of Unesco and is the National Committee for International Hydrological Programme (IHP) of Unesco. In pursuance of its objective of preparing and periodically updating the state-of-art in hydrology in the world in general and India in particular, the committee invites experts in the country to prepare these reports on important areas of hydrology.

The Indian National Committee on Hydrology with the assistance of its erstwhile Panel on Water Quality, Erosion and Sedimentation has identified this important topic for preparation of this state-of-art report and the report has been prepared by Dr. R.S. Varshney, Former Engineer-in-Chief, Irrigation Department, U.P. The guidance, assistance and review etc. provided by the Panel are worth mentioning. The report has been finalised by Dr. K.K.S. Bhatia, Member Secretary of the Indian National Committee on Hydrology.

It is hoped that this state-of-art report would serve as a useful reference material to practicing engineers, researchers, field engineers, planners and implementation authorities, who are involved in correct estimation and optimal utilization of the water resources of the country.

(S.M. Seth)
Executive Member, INCOH
& Director, NIH

Roorkee

Table of Contents

Section	Page
The Problem	**1**
-Sedimentation in Reservoirs	1
* Mechanism of sedimentation	1
* Factors affecting sedimentation	3
* Size of watershed area	3
* Sedimentation delivery ratio	5
* Relief-length ratio	5
-Effect of Sedimentation of Reservoir Functions	5
* Loss of storage and service	5
* Deposition at outlet gate	8
* Aggradation above reservoirs	8
* Degradation below reservoirs	8
Density of Sediment Deposited in Reservoirs	**9**
-Sediment Characteristics	9
-Density of Deposited sediments	9
Trap efficiency of Reservoirs	**17**
-Definition	17
-Methods to Determine Trap Efficiency	17
-Trap Efficiency of Some Indian Reservoirs	22
Estimate of Sedimentation Rates in Reservoirs	**25**
Actual Sedimentation Rates in Indian Reservoirs	**43**
-Sedimentation in Indian Reservoirs	43
-Reduction in Siltation Rate with Passage of Time	46
Distribution of Sediment in Reservoirs	**53**
-General	53
-Association of Flood Plain and Channel Deposit	53
-Methods for predicting sediment Distribution	56
-Actual Sediment Distribution in Different Reservoirs	66

Life of Reservoirs **73**

-Different Aspects of Life of Reservoir 73
- Review of Reservoir Performance and Economic Life 74
- Evaluation of Useful Life of Reservoir 76
- Comprehensive method to Evaluate Life of Reservoir 83
- Practices Followed to estimate Life of Reservoirs 100

Delta Formation-Analytical and Mathematical Models **103**

-Delta Formation 103
-Analytical Models 103
-Mathematical Models 105

References **107**

Appendix-I **112**

-Statement showing the Data in respect on
32 Indian Reservoirs

THE PROBLEM

SEDIMENTATION IN RESERVOIRS

Sedimentation in reservoirs is a difficult problem for which an economical solution has not yet been discovered, except by providing a "dead storage" to accommodate the deposits during the life of a dam. Disintegration, erosion, transportation and sedimentation are the different stages leading to silting of reservoirs.

As water enters a reservoir, its velocity diminishes because of the increased cross-sectional area of the channel. If the water stored in the reservoir is clear and the inflow is muddy, the two fluids have different densities and the heavy turbid water flows along the channel bottom towards the dam under the influence of gravity (Fig. 1.1). This condition is known as "stratified flow" and the underflow is called a "density current". In a general sense, a density current may be defined as a gravity flow, a fluid under, over, or through a fluid or fluids of approximately equal density. From figure 1.1 it may be seen that the depth of the turbid flow increases to the point where the density current is established after which it tends to decrease again. The magnitudes of these relative change and their effects upon sediment deposition depends on many factors such as reservoir shape, channel slopes, relation of outflow to inflow and density differences. As a rule, however, conditions are such that density currents move very slowly. In Lake Mead U.S.A., for example, maximum observed velocities are near 3 km p h, while the average velocity is somewhat less than 1.5 km p h.

Mechanism of Sedimentation : In many respects deposits in a reservoir resemble those in a delta, made by a stream where it discharges into a lake or sea. These deposits are (i) bottom set beds, consisting of the fine sediments brought in by the stream (ii) the foreset beds formed of the coarser sandy sediments (iii) top set beds consisting of coarser particles and (iv) density current deposits (Fig. 1.2).

As a general rule, progressively smaller sizes of material will be deposited beyond the delta front, resulting in a gradual downward slope of the reservoir bed. If the stream carries an appreciable wash load, however, much of this material may not settle out as the cross-sectional area of the stream increases. Further more, the suspension may not mix completely with the clear water of the reservoir because of its difference in specific gravity. The gravity underflow (density currents) moves through the entire length of the reservoir. Unless this portion of the flow is discharged at the dam, it will collect as a submerged pool, forming an almost level floor in the deepest part of the reservoir, where it gradually compacts.

The sedimentation is a product of erosion in the catchment area of the reservoir and hence lesser the rate of erosion the smaller is the sediment load entering the reservoir.

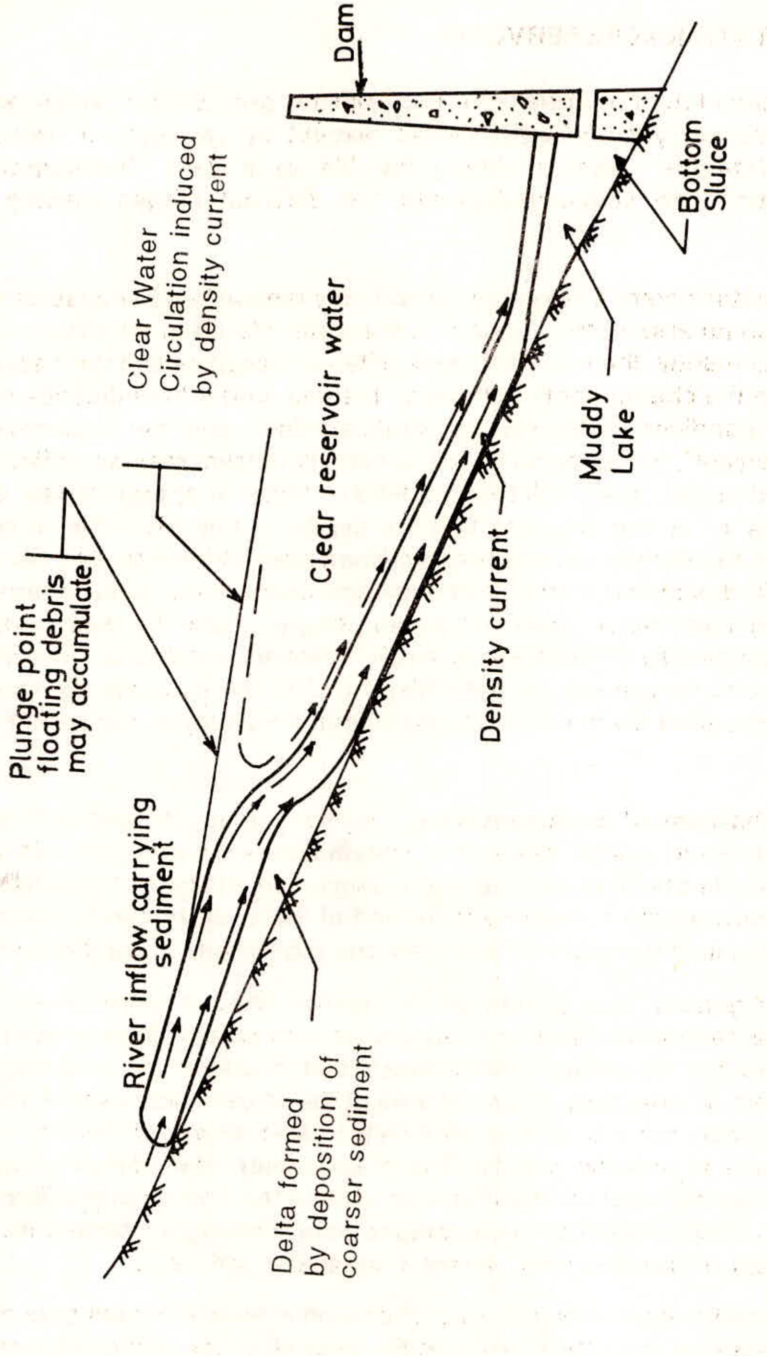


Figure 1.1 Conceptual sketch a density current and muddy lake in a reservoir

Factors Affecting Sedimentation

The following factors affect sedimentation :

(i) Extent of catchment area and the friable nature of the different zones.

(ii) Amount of sediment load in the rivers.

(iii) Type of rainfall and snowfall in each zone.

(iv) Mean monthly and annual run-off from catchment or subcatchment.

(v) Monthly and annual run-off from catchment or subcatchment.

(vi) Slope of each zone of catchment.

(vii) Vegetation in each zone of catchment.

(viii) Geological formation of each zone: estimated relative weathering and erosion with due regard to climatic conditions.

(ix) Presence of upstream reservoir and extent of trapping of sediment therein.

(x) Amount of sediment flushed out through sluices.

(xi) Degree of consolidation of accumulated sediment depending upon the extent of exposure to air, sun and wind.

(xii) Operation schedule of the reservoir.

The capacity inflow ratio and the sediment content in the inflow have a complete range of inter play and the rest of the factors are alı modifiers.

Some factors influencing sedimentation rates are discussed herein.

Size of Watershed Area

As a general rule the average rate of sedimentation decreases as the size of the drainage area increases (Fig. 1.3). Also the larger the watershed, the lesser is the variation between the rates. Observations for Indian catchments are given in Chapter 4.

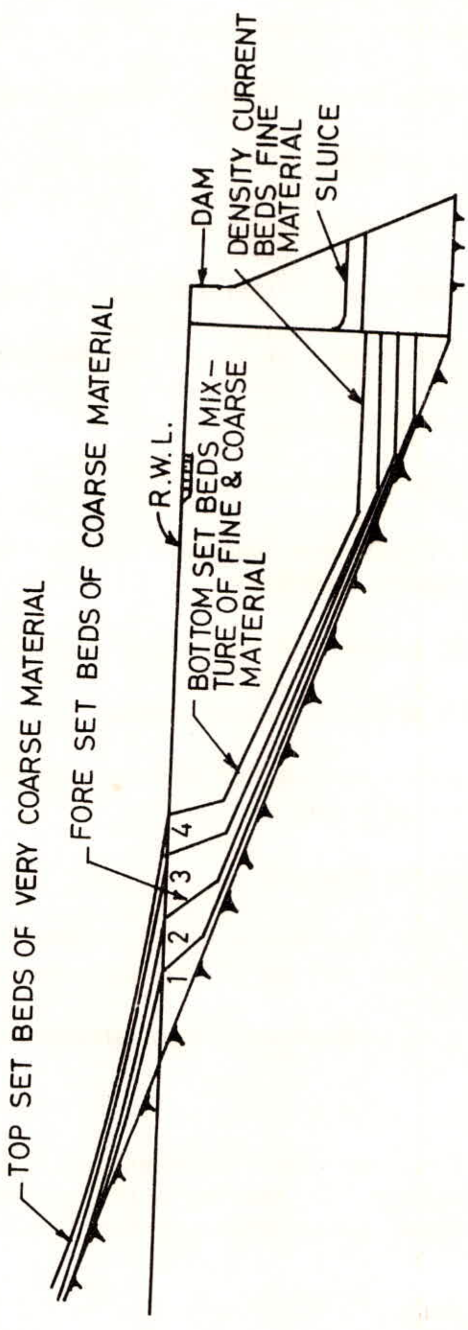


Figure 1.2 Sediment deposits in a reservoir

Sedimentation-Delivery Ratio

Figure 1.4 shows the curve of sediment delivery ratio (Ratio between the amount of sediment yield and the cross erosion in watershed) with the area of watershed for the region Black Land and Prairies Land Resources Area Texes U.S.A. Higher sediment delivery ratio is associated with smaller catchments. As one moves upstream, the drainage basin area decreases and the topographic factors that promote sediment-delivery become more intensified resulting in higher sediment-delivery ratio.

Relief Length Ratio

Some investigations have found the watershed slope to be a significant factor influencing the sediment delivery ratio and sediment yield. The relief length ratio can be determined from the existing topographic maps.

$$R = \frac{h}{L} \qquad 1.1$$

where

R = relief ratio

h = relief of watershed, i.e. difference between the minimum and maximum elevation.

L = maximum length of watershed.

Figure 1.5 shows the sediment-delivery ratio against relief length ratio for Red Hills and Southern Piegment Land Resource Area Texas USA.

EFFECT OF SEDIMENTATION ON RESERVOIR FUNCTION

Loss of Storage and Services (R. I. Strand 1974)

Sedimentation impairs the useful life of a reservoir and directly affects the services dependent upon the water storage. The progressive reduction of the active storage capacity may reflect on the outputs from the reservoir in the following ways:

1) It may reduce the dump or secondary output.

2) It may reduce availability of firm water in marginal years by increase in both the number and quantum of failures.

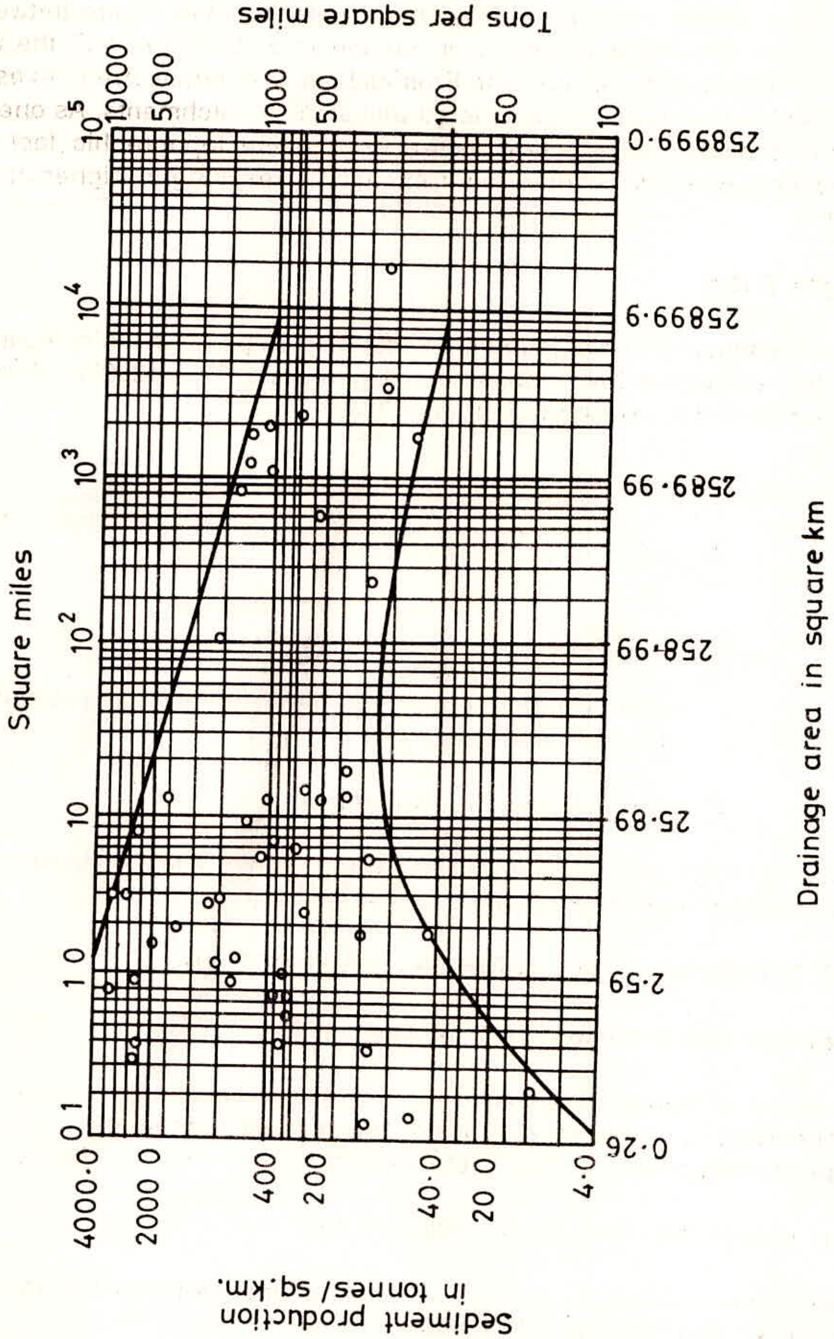


Figure 1.3 Sediment production rates in the West Gulf Drainage Region (U.S.A.)

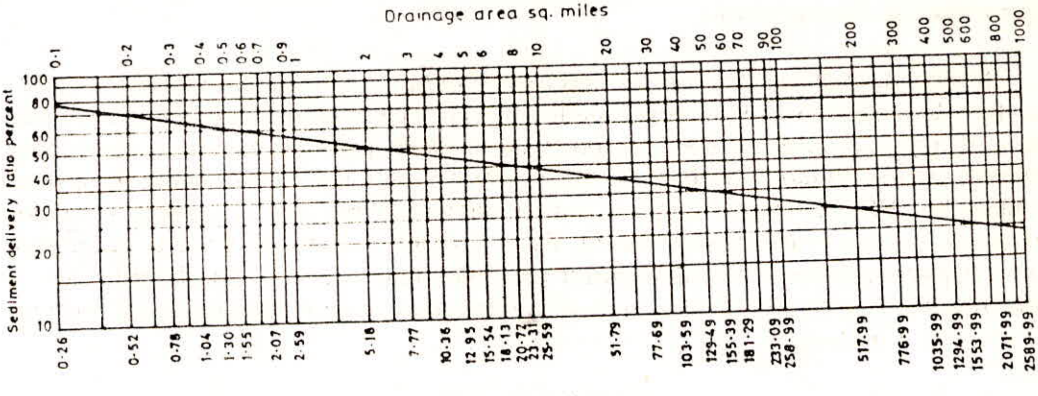


Figure 1.4 Sediment delivery ratio curve-erosion from all sources

Data from Black Land and Prairies Land Resources Area-Texas.
Recommended use : Where erosion is from fine and medium textured soils.
[U.S. Deptt. of Agriculture, Soil Conservation Services]

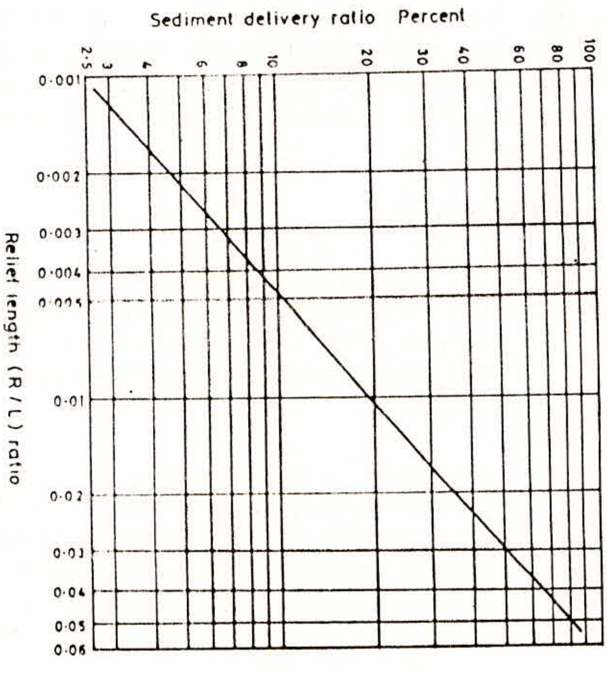


Figure 1.5 Sediment delivery ratio curve-erosion from all sources

Data from Red Hills and Southern Piegment Land Resource Area.
Recommended use : Where erosion is from fine and medium and coarse textured soils.

Deposition at Outlet Gates:

Distribution of sediment is an important consideration in the location of gates or outlets to avoid area where rapid sedimentation might occur. Deposition may also occur at gates located at the dam particularly during period of heavy drawdown. According to the annual reports of the Puerto Rico Water Resources Authority, a flood on May 19, 1940 brought down so much sediment into the Guayabal Irrigation Reservoir, on the south west of Puerto Rico, that the outlet works were completely buried. Operations were crippled and it was impossible for several days to deliver water needed for irrigation. The reservoir was subsequently dredged and the dam raised by 4.9 metres.

Sediment accumulation at the dam face may increases the loading on the masonry/concrete dam structure beyond what has been provided for.

Aggradation above Reservoirs:

Deposition in delta and above crest elevations of reservoirs may cause serious aggradation upstream from the reservoir and braided river pattern may result and this may be unsightly. Such aggradation results in reduced capacity of upstream channels to contain flows which create more frequent or permanent flooding, additional submergence, elevating of groundwater tables and swamping of lands in the valleys and many actually bury under sediments. Tree growth in the delta lends increase evapotransipiration.

Degradation below Reservoirs:

Where the outflow has sufficient tractive force to initiate movement of materials in the channel below the structure, channel degradation takes places. Numerous and prolonged outflows of clear water from reservoir into channels with unlimited depths and reaches of transportable materials result in rapid degradation which may extend for may kilometres downstream.

The operation constraints for a reservoir may necessitate certain minimum reservoir level and filling generally starts at around same level or range of levels. Over a period of years, large deposits of sediment may be built up in the reservoir. The depth of sediment upstream and downstream of this location is small, resulting in a sort of hump in the reservoir bed. This hump acts as a natural barrier to the flow of sediment closer to the dam. The deleterious effect of this hump formation is the early reduction of live storage capacity.

Sedimentation increases the turbidity of water resulting in environment problems like deterioration of water quality and reduction of visibility in the reservoir water for fish survival.

DENSITY OF SEDIMENT DEPOSITED IN RESERVOIRS

SEDIMENT CHARACTERISTICS

A knowledge of the sediment characteristics, grain size distribution and density is necessary to provide for sedimentation provision in the design of a reservoir. The grain size distribution is important in (i) assigning a trap efficiency value to the reservoir (ii) predicting the horizontal and vertical distribution of sediment to determine sediment requirements for specific allocated storage and (iii) predicting the ultimate volume-weight relationship for determining space required for the sediment deposited in the reservoir.

The details of particle characteristics, shape and size, grain size distribution and specific weight of sediments are discussed in any standard book on Soil Mechanics and may be referred to.

In case of reservoir, the density of deposit changes with time and needs careful determination as this governs the useful life of a reservoir.

DENSITY OF DEPOSITED SEDIMENT

The unit weight of the deposited sediment needs to be computed under two conditions viz (i) the initial unit weight of the deposited sediment, and (ii) the unit weight of deposited sediment with time.

J.M. Lara and E. Pemberton:

To compute the initial weight of the deposited sediment, Lara and Pemberton developed a method for estimating the same when the size analysis of the incoming sediment and the proposed reservoir operation are known. Reservoir operations were classified according to different types as per Table 2.1.

Table 2.1 : Classification of Reservoirs on the Basis of its Operation-after Lara and Pemberton

Type	Reservoir Operation
I	Sediment always submerged or nearly submerged.
II	Normally moderate to considerable reservoir drawdown.
III	Reservoir normally empty.
IV	River bed sediments.

The initial unit weight of the sediment deposits can be computed from

$$W = 16.02\,(C_c P_c + C_m P_m + C_s P_s) \qquad 2.1$$

where

W = initial unit weight of sediment deposit (kg/m^3)

C_c, C_m, C_s = coefficients of clay, silt and sand respectively which may be obtained from Table 2.2.

P_c, P_m, P_s = percentage of clay, silt and sand respectively in the incoming sediment load.

Table 2.2

Values of Coefficients of Clay C_c, Silt C_m and Sand C_s

Reservoir Type	C_c	C_m	C_s
I	26	70	97
II	35	71	97
III	40	73	97
IV	60	73	97

The following are some of the methods to determine density of deposits with time.

E.W. Lane & V.K. Koelzer's Equation (1943):

They have given the following general equation, based on time and the grain size constituents of sediment, for estimating the unit weight of sediment for design purposes.

$$W = W_1 + K \log t \qquad 2.2$$

where

W = unit weight or density of sediment after t years of compaction.

W_1 = initial unit weight considered at the end of 1 year.

K = constant.

Note : The above equation can also be written in the form (after M.A. Gill 1988).

$$W = W_1 t^n \qquad 2.3$$

Table 2.3 gives the various values of W_1 and K for different types of material and different conditions of reservoir operations. The values of n in equation 2.3 are also given.

Table 2.3

Design Density Values (kg/m³) for Different Soils

	Sand			Silt			Clay		
Reservoir Operation	W_1	K	n	W_1	K	n	W_1	K	n
Reservoir always submerged or nearly submerged.	1490	0	0	1041	91.3	0.0356	481	256.3	0.1576
Normally a moderate reservoir drawdown	1490	0	0	1185	43.3	0.0153	731	171.4	0.083
Normally considerable reservoir drawdown	1490	0	0	1266	16.0	0.0054	961	96.1	0.0396
Reservoir normally empty	1490	0	0	1314	0	0	1250	0	0

C.R. Miller's Refinement (1953):

Miller found that the Lane and Koelzer formula indicates too high initial values. He modified the formula and gave the following equation:

$$W_t = W_1 + 0.434\,K\left[\left(\frac{t}{t-1}\right)(\ln t)-1\right] \qquad 2.4$$

where

W_t = average unit weight after t years of reservoir operation (kg/m³)

W_1 = initial unit weight as derived from equation 2.1

K = constant based on the type of reservoir operation and sediment size analysis obtained from Table 2.4.

Table 2.4 Values of W_1 and K-after Miller

Reservoir operation	Sediment Material: Sand W_1	Sand K	Silt W_1	Silt K	Clay W_1	Clay K
a) Sediment always submerged or nearly submerged	1410	0	1073	91.31	208	256.32
b) Normally a moderate reservoir drawdown	1410	0	1218*	43.25	-	171.41
c) Normally considerable reservoir drawdown	1410	0	1298*	16.02	-	96.12
d) Reservoir normally empty	1410	0	1346*	0	-	0

Estimated: Sand $1.0 > d > 0.05$ mm
Silt $0.05 > d > 0.005$ mm
Clay $d < 0.005$ mm

Miller refined the data of Lane and Koelzer to determine average unit weight of deposits for a given period of time. The condensed equations shown in Table 2.5 were developed by him for the purpose.

Table 2.5 Equations for Converting Lane and Koelzer's unit weight W_1 to average weight for different periods of time (years indicated by subscripts).

$W_{10} = W_1 + 0.675\,K$	(2.5)		$W_{60} = W_1 + 1.372\,K$	(2.10)	
$W_{20} = W_1 + 0.938\,K$	(2.6)		$W_{70} = W_1 + 1.438\,K$	(2.11)	
$W_{30} = W_1 + 1.093\,K$	(2.7)		$W_{80} = W_1 + 1.493\,K$	(2.12)	
$W_{40} = W_1 + 1.210\,K$	(2.8)		$W_{90} = W_1 + 1.542\,K$	(2.13)	
$W_{50} = W_1 + 1.298\,K$	(2.9)		$W_{100} = W_1 + 1.588\,K$	(2.14)	

U.S. Soil Conservation Service's Data:

Table 2.6 shows the relationship of specific weight to grain size distribution and reservoir operation given by U.S.S.C.S for general design purposes (50 year design period) of flood water retarding and multiple purpose reservoirs.

Table 2.6 Range in Specific Weight - After U.S.S.C.S.

	Grain Size	Permanently submerged kg/m^3	Aerated kg/m^3
1.	Clay	640-960	960-1280
2.	Silt	880-1200	1200-1360
3.	Clay Silt mix (equal parts)	640-1040	1040-1360
4.	Sand Silt mix (equal parts)	1200-1520	1520-1760
5.	Clay Silt Sand mix (equal parts)	800-1280	1280-1600
6.	Sand	1360-1600	1360-1600
7.	Gravel	1360-2000	1360-2000
8.	Poorly sorted sand & gravel	1520-2080	1520-2080

U.S.B.R. Criteria (1951):

T. Maddock and W.R. Borland (1951) have reported the average volume weight of sediment deposited over a 50 year period adopted by USBR which fails within the following criteria.

1.	Less than 10% sand, infrequent drawdown of reservoir.	800-960 kg/m^3
2.	Less than 10% sand, frequent drawdown of reservoir	880-1040 kg/m^3
3.	10% to 25% sand, infrequent drawdown of reservoir	880-1040 kg/m^3
4.	10% to 25% sand, frequent drawdown of reservoir	960-1120 kg/m^3
5.	25% to 50% sand, infrequent drawdown of reservoir	960-1120 kg/m^3
6.	25% to 50% sand, frequent drawdown of reservoir	1040-1200 kg/m^3

7.	50% to 75% sand	1200-1360 kg/m^3
8.	Over 75% sand	1360-1600 kg/m^3
9.	Boulders, grand, sand, very little fine material	1600-1760 kg/m^3

L.C. Gottschalk's equation (1952):

On the basis of experiments on Pelham Lake, L.C. Gottschalk gave the following relation.

$$W = 366 + 57.27\ d + 0.02067\ e^{2.28} \quad (2.15)$$

where

W = specific weight of sediment in kg/m^3

d = depth of sediment in metre

e = base of natural logarithm

U.S. Department of Agriculture's values:

1.	Water stored temporarily and the deposited water is subject to shrinkage during long periods	1400 kg/m^3
2.	Water stored for winter and summer use and the deposit is exposed for sometime only	1100 kg/m^3
3.	Reservoir level is maintained high and exposure and shrinkage do not take place	500 kg/m^3

Data of Lake Mead (Hoover Dam USA)

The actual observations of densities of sediment observed in Lake Mead of different depths are shown in Figure 2.1.

Data of Indian Reservoirs : (CBI & P. T.R. No. 19. Sept 1980)

The following results (Table 2.7) have been obtained in Indian Reservoirs after analysis of number of samples.

Reproduced From Fig.6 of paper " A Global perspective of sediment control measures in reservoirs" by Gregory, L. Morris, WAPCOS- Workshop on Management Reservoir sedimentation 27-30 June 1991 New Delhi.

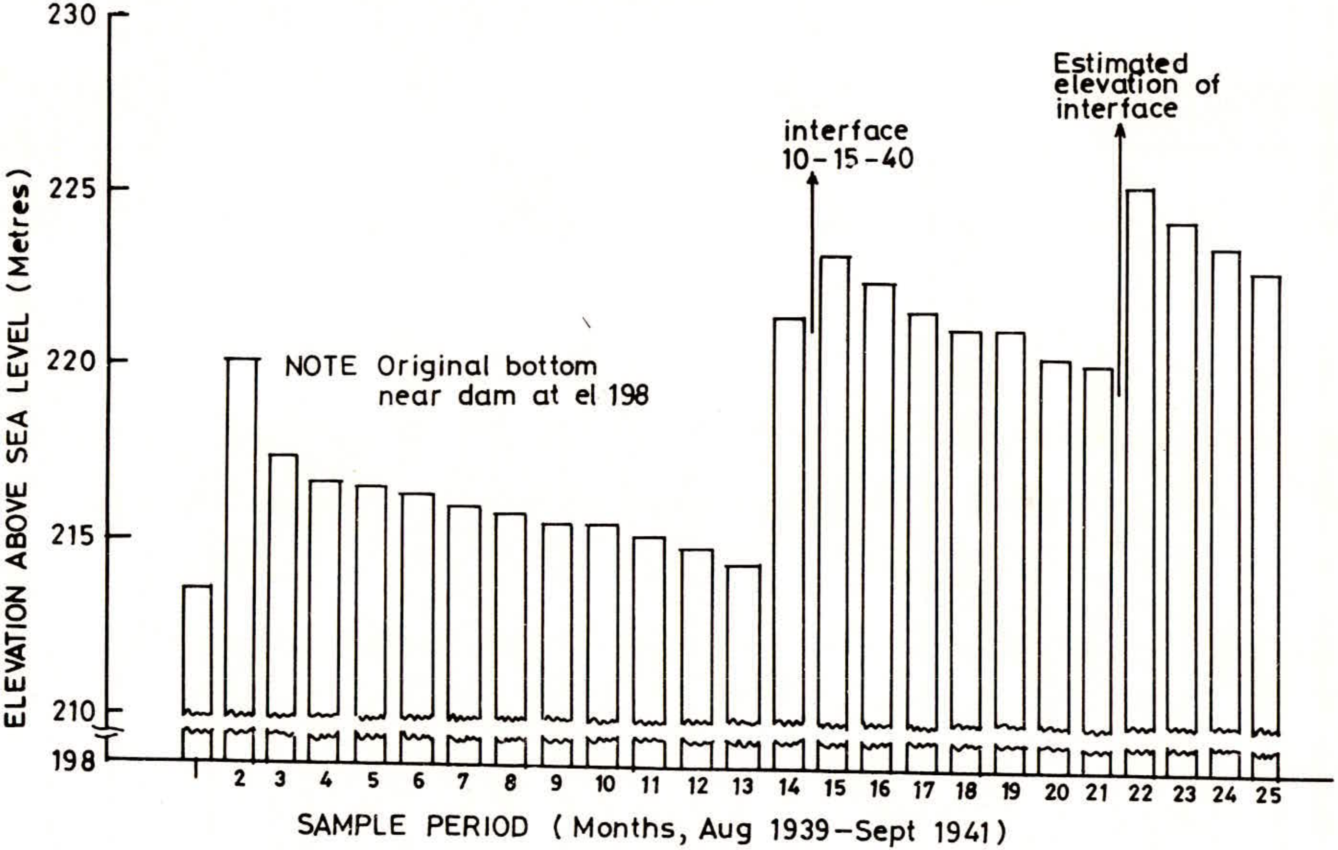


Figure 2.1 Changes in the thickness and density of the muddy pool in the bottom of Lake Mead (Bell, 1942). The numbers in each bar give sediment concentrations within the muddy lake (g/l) as a function of depth

Table 2.7 : Density Observations in Indian Reservoirs and in Mangla Reservoir

Reservoir	Density (kg/m³)	Reservoir	Density (kg/m³)
Mayurakshi	801-1121	Matatila	721-1330
Maithon	513-1714	Panchet hill	561-1762
Nizamsagar	481-1490	Shivaji Sagar	817-1314
Bhakra	1201-1650	Mangla (Pakistan)	1301-1342

TRAP EFFICIENCY OF RESERVOIRS

DEFINITION

The actual rate of silting of a reservoir depends on many other factors, in addition to the rate of sediment production in the catchment area; they are trap efficiency of the reservoir, ratio of reservoir capacity of total run-off, gradation of silt, method of reservoir operation etc. The trap efficiency of a reservoir is defined as the ratio.

$$\frac{\text{Sediment retained in the reservoir}}{\text{Sediment brought by the stream}}$$

DIFFERENT METHODS TO DETERMINE TRAP EFFICIENCY

G.M. Brune and R.E. Allen's Work (1941)

One of the earlier studies on trap efficiency were by G.M. Brune and R.E. Allen (1941) who developed a curve relating percentage of eroded soil caught in a reservoir with capacity per square mile of drainage area. The trap efficiency values given by this method were low because they were based upon rates of erosion which were higher than sedimentation rates of reservoirs.

C.B. Brown's relation (1943, 1958)

He suggested a relation for estimating the trap efficiency of a reservoir. He plotted the data of capacity watershed ratio and percentage of sediment trapped in a number of reservoirs in U.S.A. There was considerable spread in the plot (Fig 3.1) as for arid or semi-arid regions and smaller for humid regions. This indicated that the capacity-watershed ratio should be used within definite hydrologic regions and not as an index of comparison over the country as a whole.

The design curve was represented by :

$$\eta = 100 \quad [1-1/(1+0.00021C/W)] \qquad (3.1)$$

(original formula C in acre ft, W in sq mile, Constant 0.1)

where

η = trap efficiency in percent.

C/W = capacity watershed ratio in mt^3 per sq km.

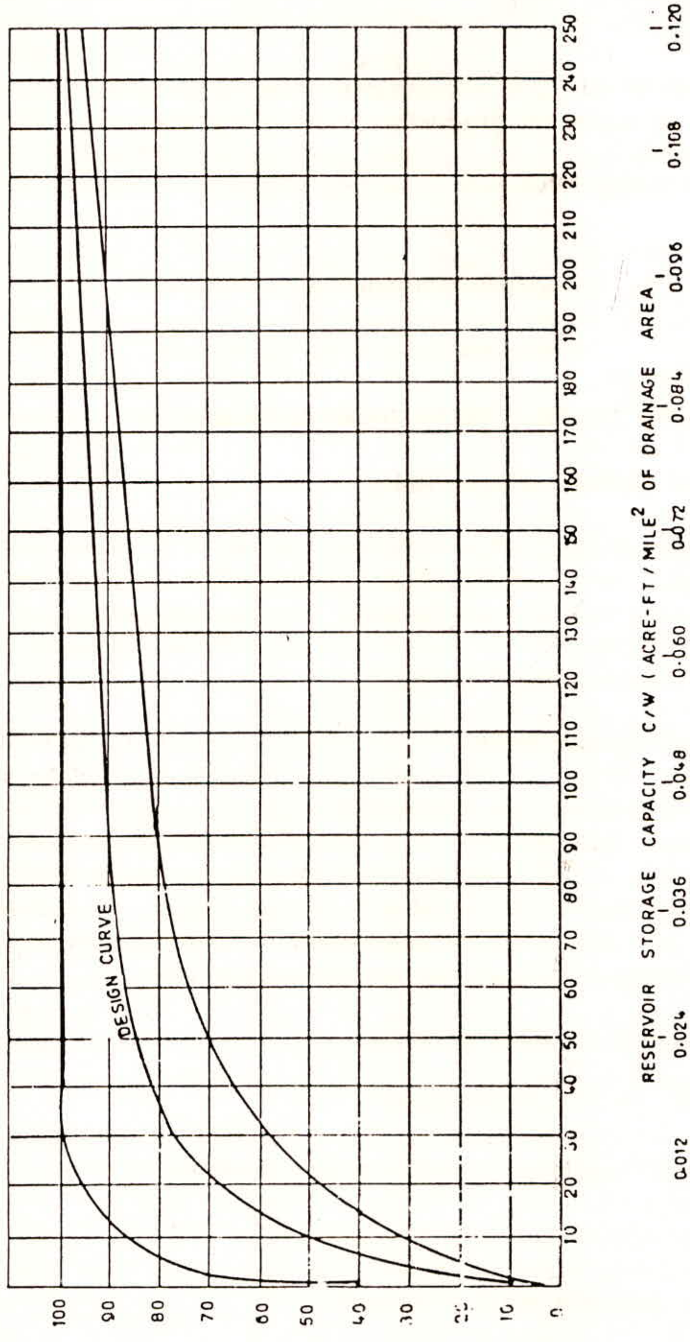


Figure 3.1 Brown's Trap Efficiency Curve (1958)

This indicates that η increases with C/W.

Allen Hazen (Trans. A.S.C.E. Vol. 77, 1914) was the first person to introduce the storage or capacity inflow ratio. He used it for determining reservoir requirement and not as an index of sediment trap efficiency. The use of C/W for determining sediment storage space has also been discussed by T. Maddock Jr. and W.M. Borland (1951).

M.A. Churchill Work (1948, 1951):

For individual reservoirs, curves can be drawn correlating trap efficiency with detention time in days. W.L. Borland prepared such a curve in 1951 for Imperial Dam Reservoir.

M.A. Churchill (1948) took into account both detention time and velocity of flow through the reservoir. He developed a "sedimentation index" which represents the period of detention divided by mean velocity. While this curve (Fig. 3.2) is very satisfactory where the data are available such information as period of detention and mean velocity is not readily available for most reservoirs.

Churchill used data form Tennessee Valley Authority reservoirs.

G.M. Brune's Curves (1953)

He has related the trap efficiency of storage type reservoirs to the remaining capacity in respect to the annual inflow (C/I) (Fig. 3.3). Their applicability for estimating trap efficiency of reservoirs of greatly differing reservoir shapes, operation and sediment characteristics remains to be demonstrated.

However, these curves serve a very useful purpose.

The C/I ratio provides a means of differentiating between the "hold-over storage reservoirs" and "seasonal storage reservoirs". Reservoirs with a C/I ratio of 1 or less may be classed as seasonal storage reservoirs and those with a ratio greater them 1.0 as hold over storage-reservoirs. Reservoirs may have a very different C/W ratios and annual inflows, yet have the same C/I ratio and the same trap efficiency, other factors being equal.

L.C. Gottschalk, who outlined methods of conducting reservoir sedimentation surveys (1952), opines (1964) about Brune's curves as very useful for estimating the trap efficiency for storage type reservoir, but that their applicability to other reservoirs remained to be demonstrated. F.Baur (1968) (quoted by W.H. Graf), who studied Alpine reservoirs, found reasonable agreement with Brune's curves but said that run-of-the-river reservoirs showed considerable deviation.

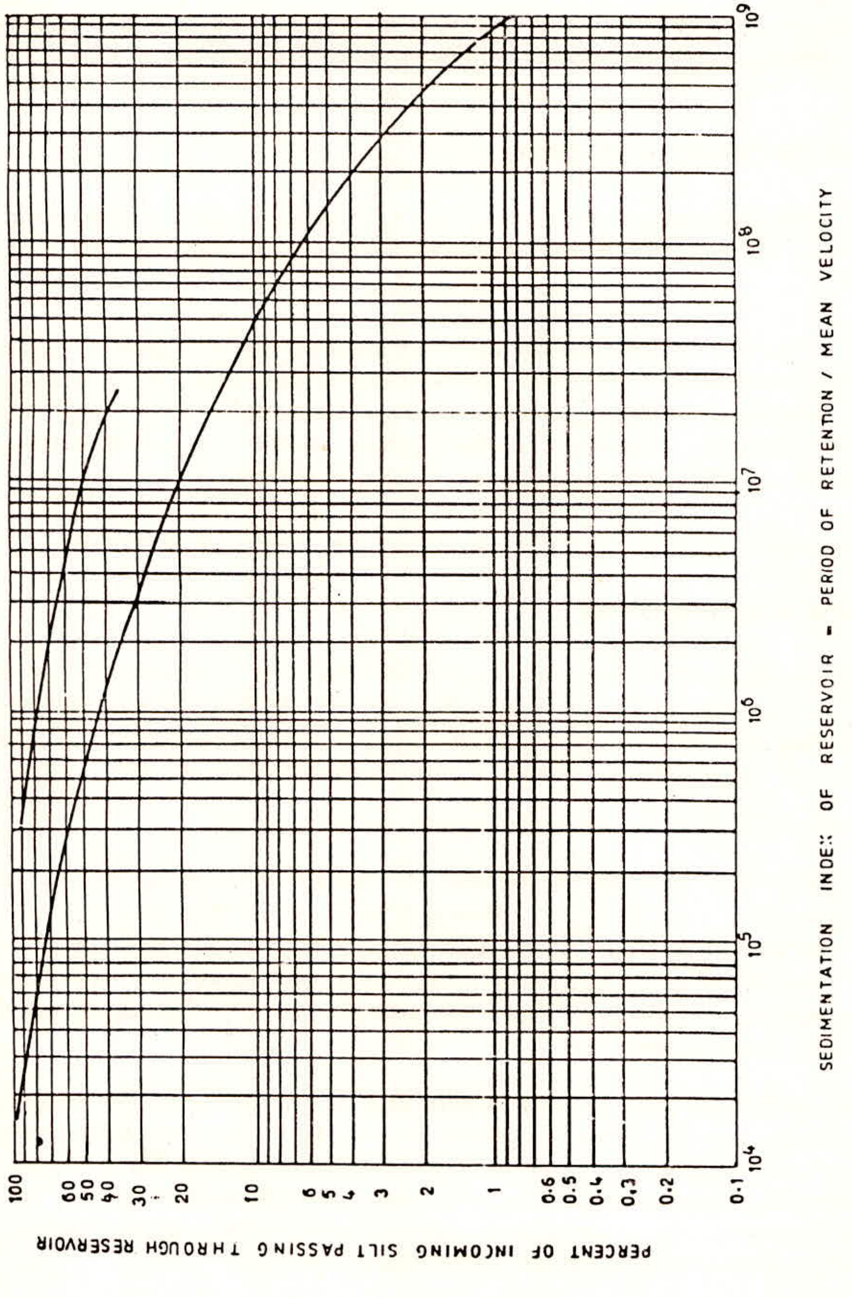


Figure 3.2 Churchill's Trap Efficiency Curves

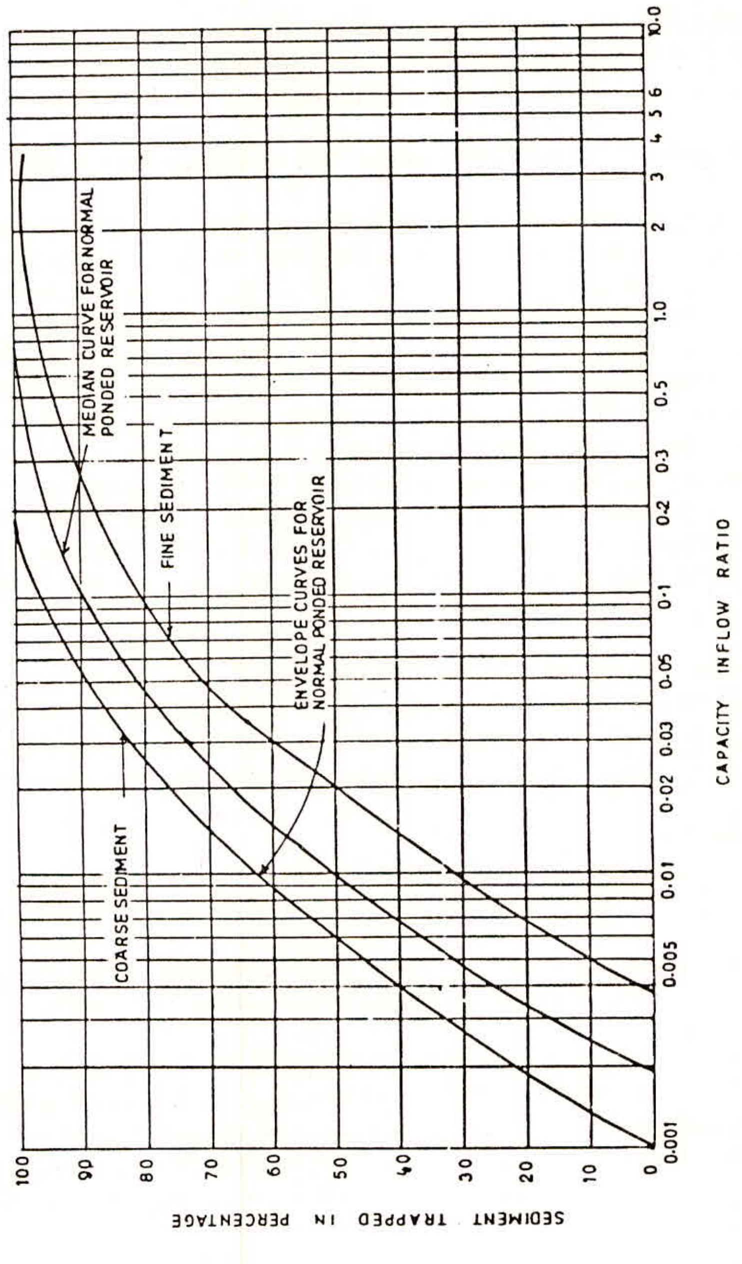


Figure 3.3 Brune's Trap Efficiency Curve

Chen's Curves (1975):

Chen presented a series of curves for various particles sizes d(mm), relating the trap efficiency to the ratio of basin area A(m^2) to the outflow rate Qo (m^2). This is shown in Figure 3.4 alongwith comparison with Brune's and Churchill's curves. It may be seen that these two well established relationships tend to underestimate trap efficiency for coarser material, but overestimate for finer material.

OBSERVATIONS OF TRAP EFFICIENCY OF SOME INDIAN RESERVOIRS

The major reservoirs constructed in the country are big ones having capacity-inflow ratio, which is a measure of detention time, ranging from 0.2 to 1.3 indicating that the reservoirs are almost 100% efficient as per Brune's curve in trapping the sediment load. Relatively few data have been obtained on the actual trap efficiency of existing reservoirs. In order to arrive at the trap efficiency of some of the reservoirs, observations on the sediment load entering into the reservoir from different sources at its head reaches and the sediment load passing through the spillway and other outlet through the dam and power house, of late, are being regularly conducted. The samples so far (upto 1978) collected have been analysed for the total sediments content and also individual grain sizes and from these observations, it has now been possible to arrive at the trap efficiency of the reservoir for the total sediment and also the efficiency in trapping the medium and fine sediments.

The observations at Matatila Reservoir (U.P.), Hirakud Reservoir (Orissa), Govind Sagar (H.P.) and Gandhi Sagar (M.P.) on sediment inflow and outflow are being conducted over a considerable period and from these observations the probable trap efficiency of each reservoir has been estimated for the present.

Matatila Reservoir

It is seen that the sand particles have 100% trap efficiency while the trap efficiency for the silt particles ranges from 70 to 90 % and for that of clay particles the trap efficiency ranges from 60 to 90%. The overall trap efficiency of the reservoir for the period 1962 to 1972 is observed to vary from 67 to 90%.

This variation may be due to the inadequacy of the frequency of the sample collection, etc., and also to the operational characteristics of the reservoir. From these considerations the overall trap efficiency of Matatila Reservoir is considered to be more than what has been arrived at . According to Brune's trap efficiency curve, this reservoir having a capacity-inflow ratio 0.2 is expected to have 90% trap efficiency.

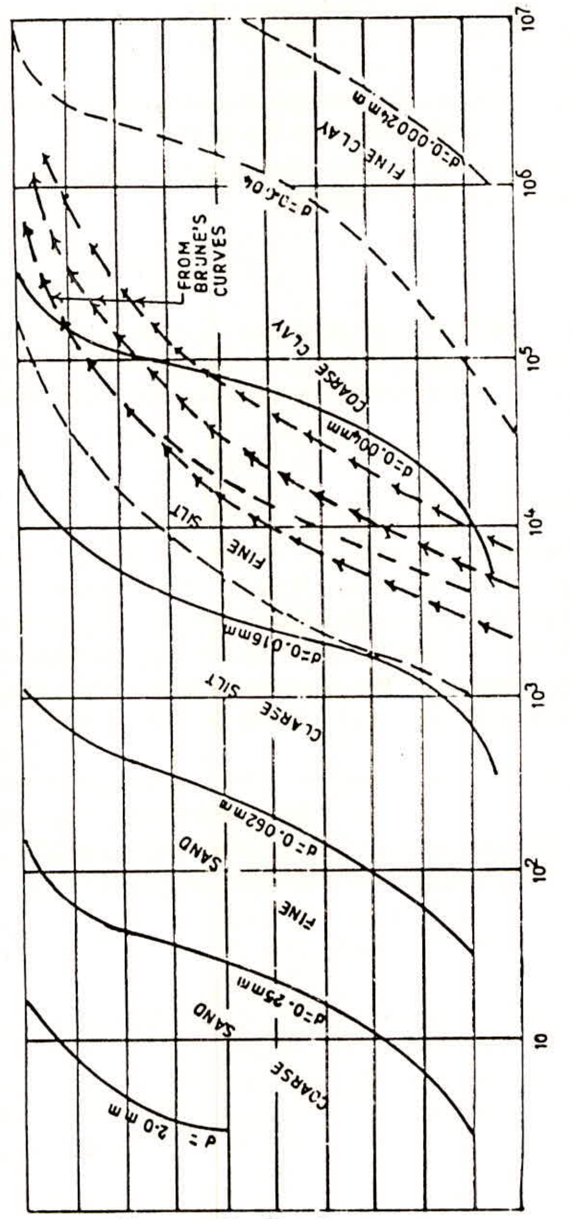


Figure 3.4 Chen's Trap Efficiency curves

Hirakud Reservoir

Actual observations carried out at Hirakud, during the period 1957 to 1967 show that most of the fine sediment ranging from 60 to 90% is retained in the reservoir. The overall trap efficiency of the reservoir is found to vary from 65 to 90% Such variation is due to the inadequacy of sampling frequency. From this, it is seen that all the incoming sediment is trapped in the reservoir and nothing substantial flows out of the reservoir through the outlets and over the spillways. The capacity-inflow ratio of Hirakud is 0.2 and according to Brune's curve a trap efficiency of about 92% is indicated for this reservoir.

Gandhi Sagar

The observations made at Gandhi Sagar for the years 1962 to 1972 show that the reservoir is having a trap efficiency of almost 100%. This reservoir has a capacity inflow ratio of 1.3 and the trap efficiency according to Brune's curve is almost 100%.

Bhakra Reservoir

The Bhakra authorities are also continuously taking suspended sediment observations both upstream and down stream of the reservoirs and from the observation the sediment retained in the reservoir has been calculated and the trap efficiency worked out. It is observed that the trap efficiency of the reservoir has been almost 99%. The Bhakra Reservoir has a capacity-inflow ratio of 0.7 and according to Brune's curve the trap efficiency is found to be above 95%.

While assessing the life of reservoir, it had been assumed that all the fine silt including clay and about 5 percent of the remaining silt would pass out of the reservoir through the outlets of the dam as density currents. From the actual observation it is seen that most of the sediment is deposited in the reservoir.

ESTIMATE OF SEDIMENTATION RATES IN RESERVOIRS

SEDIMENTATION RATE - FOREIGN RESERVOIRS.

The following are some of the relations to evaluate soil loss and sedimentation rate of reservoirs.

A.W. Zingg (1940)

He recommended the following relationship

$$X = C.S^{1.4}.L^{1.6} \qquad 4.1$$

where

X = total soil loss
S = slope
L = slope length
C = a constant

Average soil loss per unit area.

$$A = C.S^{1.4}.L^{0.6}$$

D.D. Smith (1941)

He added crop (C) and supporting practice (P) factors to the equation and proposed the following form of equation.

$$A = C.S^{1.4}.L^{0.6}.P \qquad 4.3$$

The C factor included effects of weather and soil as well as cropping system.

G.W. Musgrave Method (1947):

Musgrave and Associates of SCS have developed the following empirical equation for USLE (Universal Soil Loss Equation).

$$V_s = 6.547\times10^{-2} f_s f_c S^{1.35} L^{0.35} (P_{30m})^{1.75} A \qquad 4.4$$

where

V_s = volume of sediment deposited in the reservoir ($M.m^3$)

f_s = soil factor

f_c = cover factor

S = slope of the catchment

L = length of catchment in m.

P_{30m} = maximum 30 min. rainfall from a 2 year frequency in metre.

A = catchment area km^2

Johnson and Beev Method

$$V_s = 4.7 \times 10^{-6} f_s f_c E_c (VwQm)^{0.56} L.S. \quad 4.5$$

where

Q_m = peak flow rate m^3/sec.

E_c = erosion control practice factor, varying from 0.1 to 1.0

V_w = cummulative volume of the water inflow per unit width of the reservoir at the full reservoir level (m^3/m)

S = average initial bed slope.

Witzig Jenkins et al (1960)'s relation:

Witzig Jenkins et al have attempted to correlate the reservoir capacity, watershed ratio to annual sedimentation rate.

$$y = 0.158 \; I \; (V_o)^{0.83} \quad 4.6$$

where

y = annual silting rate in $M.m^3/100 \; km^2$ of drainage area

I = co-efficient varying from 0.00307 to 0.0375

V_o = original storage in $M \; m^3$ per km^2 of drainage area

Ecafe's curve:

Figure 4.1 is a plot of rate of silting per annum versus capacity inflow ratio for a large number of reservoirs abroad taken from U.N. (ECAFE) Flood Control Series 5. This gives a silting rate of about 3.8 ha m per 100 sq km (80 ac ft per 100 sq miles). This is low for Indian rivers.

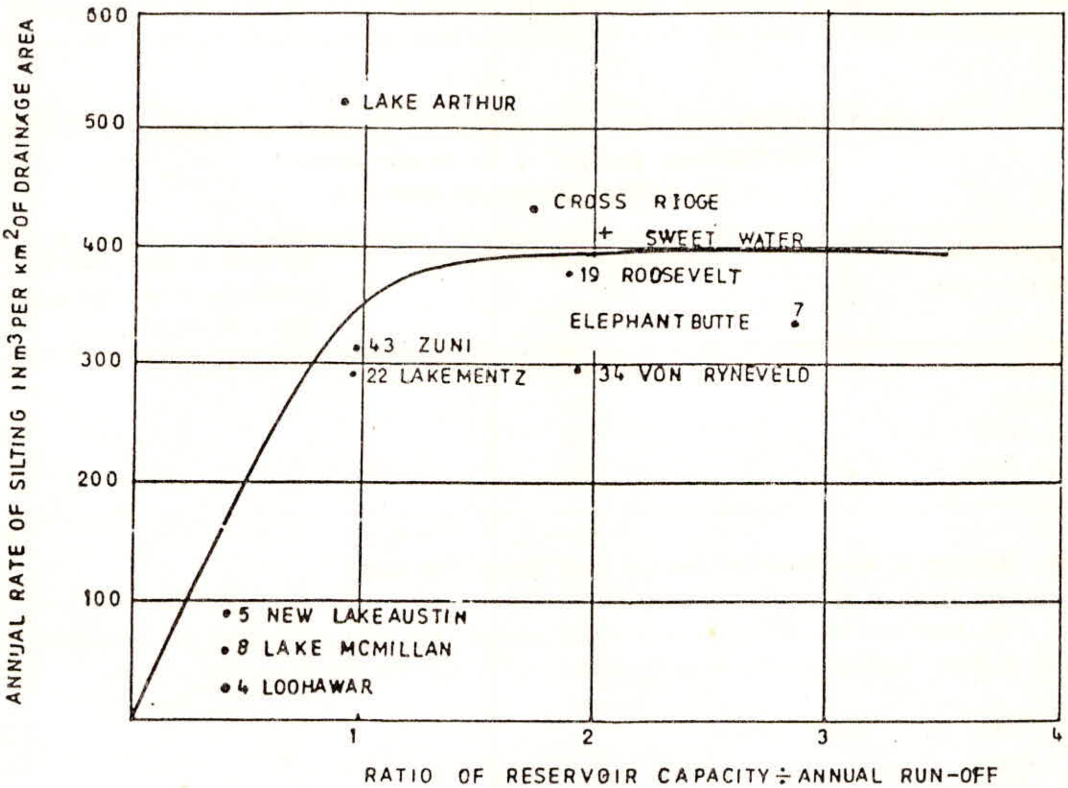


Figure 4.1 Relation between annual rate of silting per unit drainage area versus capacity in flow ratio (After Ecafe)

U.S. data (after Ven te Chow) (1964):

Table 4.1. indicates the arithmetic average of sediment production rates obtained from 100 measurements in the U.S. The Table shows that watersheds of less than 25 sq km in area on the average produce more than 7 times as much sediment per unit of drainage than watersheds exceeding 2,500 sq km in area.

Table 4.1 Arithmetic Average Sediment Production Rates for Various groups of Drainage Areas in the United States of America

Watershed size range sq km	No. of measurements	Average annual sediment production rate in ha m per 100 sq km
Under 25	650	18.0
25-250	205	7.6
250-2500	123	4.8
Over 2500	118	2.9

J.R. William's Modified Universal Soil Loss Equation:

He modified the USLE to estimate sediment yield for individual run off events from a given watershed by replacing the USLE rainfall erosivity factor with

$$R = 9.05\,(V.Qp)^{0.56} \qquad 4.7$$

where

V = volume of run off m^3

Q_p = peak discharge m^3/s

F.Fournier Method (1976):

He has suggested the following equation to compute sediment load.

$$Vs = \frac{9.317p^{5.3}\,H^{0.46 \tan S}\,A}{p^{2.65}} \qquad 4.8$$

where

p = highly monthly precipitation in metres

P = mean annual precipitation in metres

H = . mean altitude of the catchment in metres

I. Douglas Method (1978):

He has suggested an equation which has world wide application

$$V_s = K_1 [(p^2/P) - K_2)] A \qquad 4.9$$

where

K_1 and K_2 are given in Table 4.2 below

Table 4.2 Values of K_1 and K_2 in Douglas Methods.

Condition	K_1		K_2	
	S<1:100	S>1:100	S<1:100	S>1:100
p^2/P<20 mm	0.00228		8.106	
p^2/P>20mm	0.01		17.529	9.789
$\frac{p^2}{P}$<600mm		0.0195		
200mm<P <600mm		0.0341		8.037

V.S. Lapshenkov (1979) Procedure :

The general pattern of reservoir sedimentation is described by Lapshenkov as below:

$$Vx,\ t = Vx,\ t_\alpha (1\text{-}e^{-t/Ex,t}) \qquad 4.10$$

where

V_x, t = volume of deposit at reach x and time t

V_x, t_α = ultimate volume of deposits in reach x

E_x, t = sedimentation index.

Soil Conservation Service (U.S.A.) Procedure :

$$V_s = KA^{0.8} \quad 4.11$$

Knowing known values of annual sediment load V_s and area A for a surveyed reservoir, K could be evaluated.

Sedimentation Rate for Chinese Catchments:

Jiang Zhonshan and Song Wenjing's Relation (1980)

They analysed data of small water sheds (0.18-187 km^2) and suggested the relation.

$$Vs = 0.37\ M^{1.15}\ J.K.P. \quad 4.12$$

where

Vs = sediment yield caused by one storm in a catchment (t/km^2)

M = total volume of run off during a single flood m^3/km^2

J = mean slope in the catchment.

K = soil erodibility coefficient, an index indicating contents of sand and silt in loess.

P = coefficient of vegetative effect.

Mou Jinze et al Equation (1980):

They studied 246 floods in Chaba gully and gave the relation.

$$V_s = 0.25\ (M+Q_p)^{1.07}\ J^{0.2}\ L^{0.4} \quad 4.13$$

where

Q_p = peak discharge rate m^3/km^2

L = length of watershed (km)

SEDIMENTATION RATE-INDIAN RESERVOIRS

Various researchers have given sedimentation rates in Indian reservoirs, based on actual sedimentation data and sediment carrying capacity of inflowing rivers:

Dr. Khosla's findings (1953):

The earlier design of reservoirs in this country were based on the silting rate as suggested by Dr. A.N. Khosla which was on an average of 3.6 ha m per 100 sq km (75 ac ft per 100 sq miles) of catchment area. The recent surveys carried out on some of the Indian reservoirs reveal that the actual silting experienced by them has been much higher. There are various factors for such high rate, e.g. fast deterioration in the watershed, man's intrusion due to development activities, forest fires, overgrazing, unwise agriculture practices etc. Out of 38 points on which Dr. Khosla gave his enveloping curve, only 5 points pertained to data of Indian reservoirs. The catchments of these reservoirs were very big but the capacities were small. His curve conforms to the relation.

$$y = 32/A^{0.72} \qquad 4.14$$

where

y = annual silting rate in ha m per 100 sq km

A = catchment area at the site in sq km.

D.V. Joglekare's curve (1960) :

Dr. D.V. Joglekar has given an envelopping curve.

$$y = \frac{59.7}{A^{0.24}} \qquad 4.15$$

R.S. Varshney's Regional Enveloping Curves (1970, 1986) :

The actual silting data collected so far in India has been plotted and enveloping curves have been given by R.S. Varshney. Based on these plots, statistical relations have been worked out.

Since rivers to the north of Vindhyas exhibit distinct characteristics, graphs were plotted separately for northern and southern rivers (south of Vindhyas). To assesses the silting rate for smaller reservoirs, graphs were drawn separately for reservoirs and tanks with catchment area upto 130 sq km (50 sq miles) and greater than 130 sq km.

Relations for northern catchments/reservoirs are as below:

(i) For mountain rivers:

$$y = \frac{39.5}{A^{0.311}} \qquad 4.16$$

(ii) For plain rivers:

$$y = \frac{39.2}{A^{0.202}} \qquad 4.17$$

Graph was drawn for reservoirs with catchment area greater than 5000 sq km (2000 sq miles). The following relation envelopes the data of silting rate.

$$y = \frac{153.4}{A^{0.264}} \qquad 4.18$$

Studies to find their enveloping annual total sedimentation with silting rates on South Indian rivers were also made for smaller (upto 130 sq km) and bigger (above 130 km^2) catchments. The following relations give the silting rate for South Indian rivers.

For catchments upto 130 sq km

$$y = \frac{46}{A^{0.468}} \qquad 4.19$$

For catchments above 130 sq km

$$y = \frac{27.7}{A^{0.194}} \qquad 4.20$$

As an extension of the work already reported by R.S. Varshney (1970), Varshney et. al. (1986), on the basis of further studies on Himalayan catchments fond that the relationship.

$$y = \frac{141}{A^{0.265}} \qquad 4.21$$

may be used for planning storage schemes in Himalayan region.

Capacity-Inflow Studies - after R.S. Varshney

It is generally held that if the capacity of the reservoir is a high percentage of the annual yield, such reservoirs suffer a higher rate of silt accumulation. An attempt was made by R.S.Varshney to plot the capacity inflow ratio versus the annual silting rate in figure 4.2 and 4.3 for Northern and Southern reservoirs. The data was meagre, however, these curves represent the average trends.

If capacity inflow ratio is high, the trap efficiency is also high. The higher silting rate with higher capacity inflow ratio does not mean a higher rate of capacity loss, as silt production depends on the catchment characteristics. Reservoirs having high capacity inflow ratio have a lower rate of depletion of capacity. Figure 4.4 shows an attempt to plot capacity inflow ratio versus annual loss of reservoir capacity.

Fig. 4.5 charts a correlation between the capacity watershed ratio and annual silting rate. This obviously shows that for the same capacity of reservoir, increase in area will mean a lower rate of silting. For example if we construct a dam of same height in the upper catchment of a river, the silting rate would be higher than when we make it of the same height on the lower reach of the river. This agrees with the erosion formulae.

The formulae and curves as presented should be used only as a guide for preliminary estimation, to be backed by comprehensive field surveys. The topographical and geological factors should be weighed carefully to reduce or increase the silting rate calculated from the formulae and curves given.

The rate of reservoir sedimentation falls off with the advance of years. This is due to consolidation and shrinkage of deposits, fall in trap efficiency and mainly due to the formation of delta on the main river as well as in the tributaries where most of the silt is trapped at higher elevation, so much so lesser amount is received into the reservoir basin. However, no correlation in this respect was possible because of less data.

V.B. Lal and S. Banerji's Equation (1976):

V.B. Lal and S. Banerji gave an equation for estimating the sediment yield per unit area of the basin by studying data obtained from five north Indian reservoirs. The equation is given below:

$$S = (1/100)\,(C/I)^{0.22}\,(I/A)^{2} \qquad 4.22$$

where

S = annual sediment yield per unit area i.e. silt index $m^3/km^2/yr$.

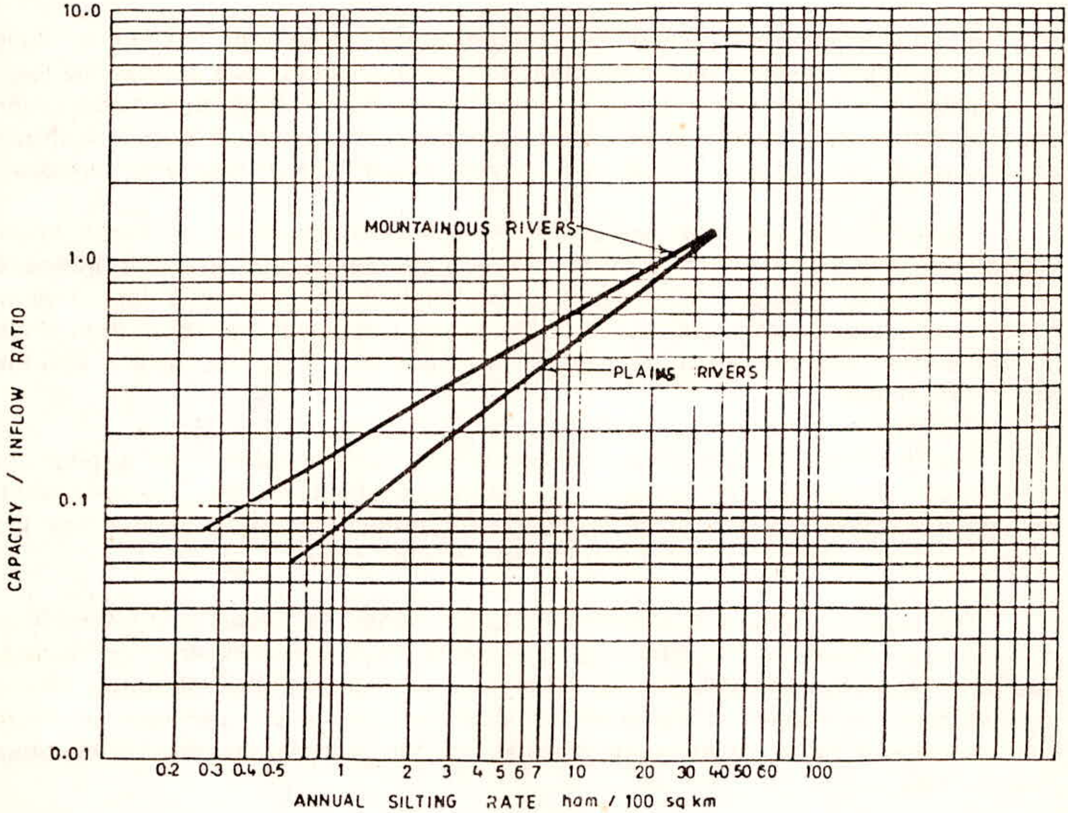


Figure 4.2 Capacity inflow ratio Vs silting rate- North Indian reservoirs -After R.S. Varshney

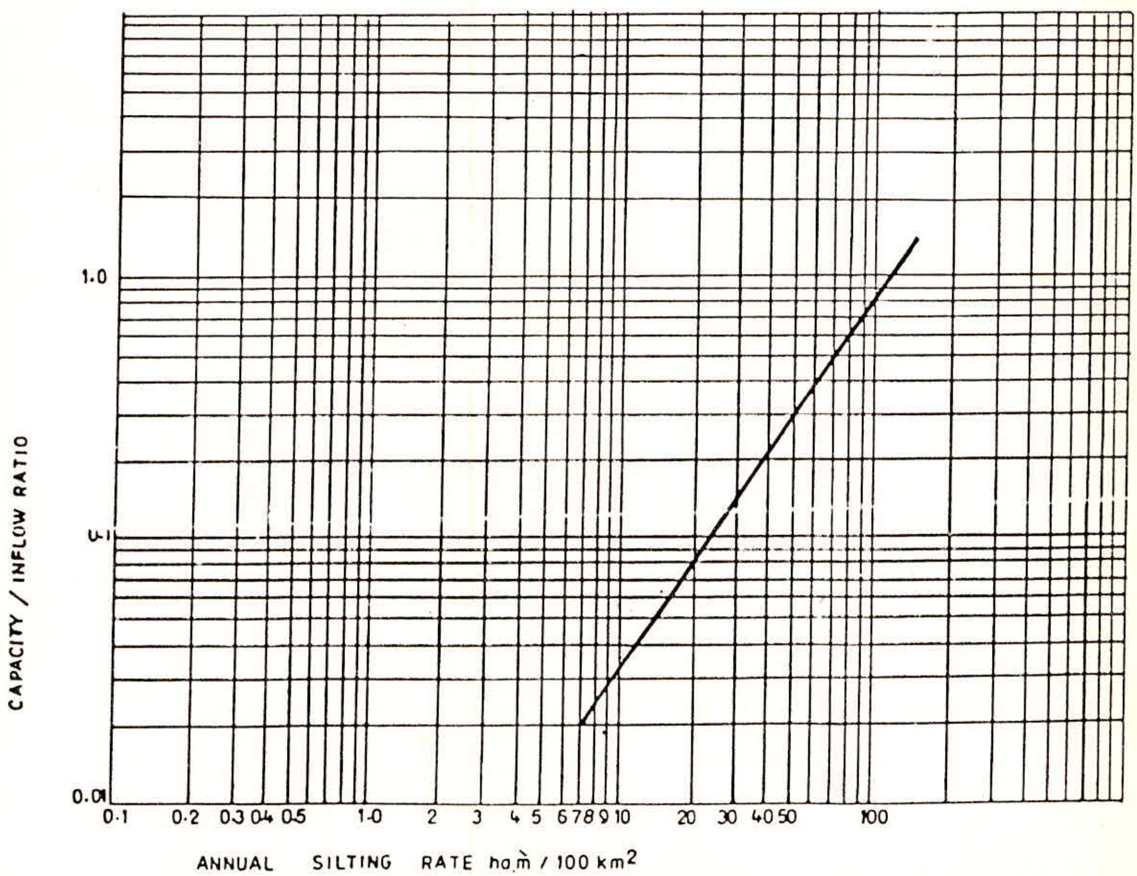


Figure 4.3 Capacity inflow ratio Vs silting rate - South Indian reservoirs -After R.S. Varshney

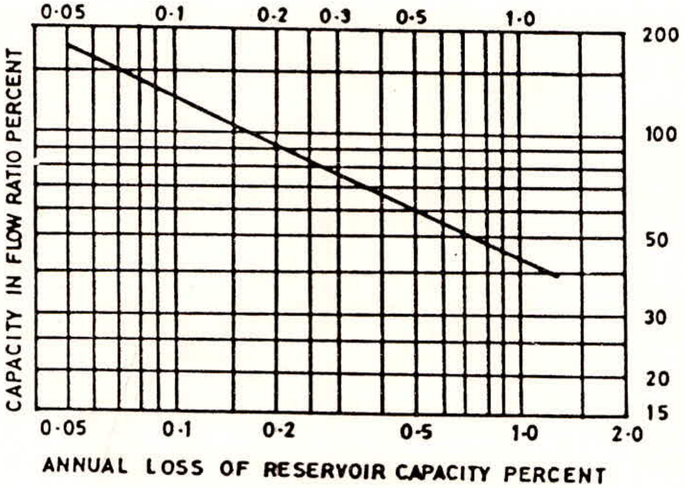
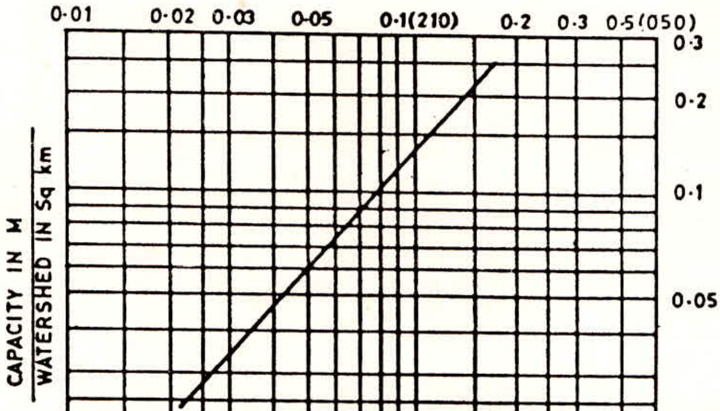


Figure 4.4 Capacity inflow ratio vs annual capacity loss



ANNUAL SILTING RATE M³/100SQ KM (ACFT/100SQ MILES)

Figure 4.5 Annual silting rate vs capacity catchment area ratio

C/I = capacity inflow ratio.

C = original capacity of reservoir in m^3.

I = average annual inflow volume ratio into the reservoir in m^3.

A = catchment area, in km^2.

P.K. Swamee's Equation (1977):

P.K. Swamee analysed the data of nine existing Indian reservoirs and proposed a method of estimating the expected sediment load in the reservoir. He related the sediment deposited in a reservoir to cumulative volume of water inflow per unit width of the reservoir at the full reservoir level and the average initial reservoir bed slope. The best fit equation is

$$(V_s/B) = \quad V_B = 1.6\ (V_w)0.94\ So^{0.84} \qquad 4.23$$

where

Vs = volume of sediment deposited in the reservoir (M m^3)

B = width of reservoir at the full reservoir level (m).

Vw = cumulative volume of the water inflow per unit width of reservoir at the full reservoir level (m^3/m)

S_o = average initial bed slope.

The mean annual flows are usually available for 15 to 20 years when the Project is designed. Hence the cumulative water inflow can be obtained by sequential generation data using time series analysis. The following equation for generating data may be used:

$$Q_{i+1} = \quad Q_i r + (1-r)\ \overline{Q} + s\ (1-r^2)\eta \qquad 4.24$$

where

Q_i = mean annual water flow in the ith year (Mm^3)

Q_{i+1} = mean annual water flow in the (i+1)th year (M m^3)

s = standard deviation of given data (M m^3)

η = random normal deviate having zero mean and unit standard deviation.

r = first serial correlation coefficient of observed annual flow data.

$\overline{Q}$ = Mean annual flow.

Experience shows that the sediment load estimated through Eq. 4.28 works out very much on the higher side. It is apparent that coefficient 1.16 of Eq. 4.23 may be modified by applying the equation to the available sediment data of existing reservoirs in the region of proposed reservoir and thereafter the modified equation used for further design purposes.

B.N. Murthy's Equation (1980):

Murthy has suggested an equation for determining silt deposit in dead storage zone. (Note on Distribution of Sediment in Reservoir placed before C.B.I. & P "Committee on Sedimentation in Reservoirs" unpublished; later given in C.B.I. & P Tech. Report No. 19 Sept. 1980).

$$S = K C^n \quad 4.25$$

where

S = percent of total sediment in the dead storge

C = percent of dead storage capacity to total capacity

K and n are constants depending on the type of reservoir (see chapter 6). Their values are given in Table 4.3.

Table 4.3 Values of K and n in B.N. Murthy's Equation

	Reservoir Type	Values of K	Values of N
I	(Lake)	3.30	0.78
II	(Flood plain in foot hill)	9.33	0.56
III	(Hill)	25.12	0.35
IV	(Gorge)	32.36	0.30

C.B.I. & P Research Committee Method (1978, 1981):

Research Committee of Central Board of Irrigation and Power has suggested two tentative methods of estimating sediment accumulation in reservoirs in absence of long term records.

It may be assumed that silt accumulation is given by

$$S = KA^{3/4} \quad 4.26$$

where

S	=	silt volume in m^3/year
A	=	catchment area in km^2
K	=	constant which can be taken as 302.09 for rocky catchments 1027.09 for normal catchments 3323 for soil catchments.

However data of U.S.A. were mostly used for arriving at these equations with some data of Indian and Myanmar.

(b) For catchments over km^2 in area, the value as suggested by Dr. A.N. Khosla has been recommended.

G.Das's Work on USLE (1982):

Das, based on William's equation, proposed the following equation for estimation of sediment yield from Naula watershed of Ramganga reservoir cathcment.

$$S_y = 11.8\ (Q.q_p)^{0.257}\ K.L.S.C.P. \quad 4.27$$

where

S_y	=	the sediment yield from watershed in tonne per storm.
Q	=	the run off amount in m^3.
q_p	=	peak rate in m^3/s
K	=	soil factor in tonne/hectare/year/unit rainfall index.

Dhruv Narain and Ram Babu's Work (1983):

They used data from 17 reservoirs in India and obtained the relation for annual sedimentation rate as below:

$$T_1 = 5.5 + 11.1\ R \quad 4.23$$

where

R	=	annual run off in million ha m.
T	=	erosion rate in tonne per year.

This equation was further redefined as

$$T = 5.3 + 12.7\ R.W. \qquad 4.29$$

where W= T/A, A being catchment area in million ha.

Average value of W was found to be 1.25 M t/M ha.

Also using data from 18 river basins, the following relationship were obtained.

$$T = 0.014\ A^{0.84}\ P^{1.37} \qquad 4.30$$

$$T = 14.25\ Q^{0.84} \qquad 4.31$$

$$T = (0.342 \times 10^{-6})\ A^{0.84}\ (EI_{30})^{1.65} \qquad 4.32$$

where

P	=	average annual rainfall in cm
A	=	cathchment area in million ha
EI_{30}	=	product of average annual value of the sum of maximum 30 minute rainfall intensity in cm/hr and kinetic energy E given by

$$E = 210 + 89 \log I_{30} \qquad 4.33$$

where

E	=	tonne pr ha m.

R.J. GARDE et.al. (1983):

They analysed the data from 31 small and large reservoirs in India. Taking into account the trap efficiency, the deposited material was expressed as V_s the absolute volume of sediment yield in M m^3 per year and was related to other pertinent variable by the equation.

$$V = (1.06 \times 10^{-6})\ A^{1.29}\ P^{1.38}\ S^{0.13}\ D_d^{\ 0.40}\ F_c^{\ 2.51}\ - \qquad 4.34$$

where

S = land slope

D_d = drainage density in km^{-1}

P = mean annual rainfall in cm.

V_s = eroded material in M. m^{-3}.

F_c = erosion factor, which is related to the land use as

$$F_c = \frac{1}{\Sigma Ai} (0.20\ A_F + 0.40\ A_{UF} + 0.60\ A_A + 0.80\ A_g + A_w) \qquad 4.35$$

where

A_F = protected forest area km^2

A_{UF} = unclassed forest area km^2

A_A = arable area km^2

A_g = scrub and grass area km^2

A_W = waste area km^2

The consolidation of Ai are arbitrary.chosen. This equation gave less than + 30 p.c. error for 90% of data.

R.J. Garde and U.C. Kothyari (1985, 1986)

A more rigourous analysis of sediment yield from Indian catchments has been carried out by Garde and Kothyari. Using data from 50 small and large catchments in India, they have developed the following relationship for sediment erosion rate y in cm.

$$y = 0.02\ p^{0.60}\ F_e^{1.70}\ \overline{S}^{0.25}\ D_d^{0.10} \left(\frac{P_{max}}{P}\right)^{0.19} \qquad 4.36$$

where

P_{max} = average maximum monthly rainfall in cm

$\overline{S}$ = average catchment slope

F_e = erosion factor

where

$$S = \frac{\Sigma A_i S_i}{A}$$

$$F_e = \frac{1}{\Sigma A_i} (0.8 A_A + 0.6 A_g + 0.3 A_F + 0.1 A_W) \qquad 4.37$$

Kothyari et. al. (1986) have derived the following equation for prediction of annual sediment yield.

$$y_a = 0.02 F_e 1.7 \bar{S}^{0.25} D_d^{0.10} (\frac{P_{max}}{P})^{0.19} P_a^m \qquad 4.38$$

y_a = annual sediment yield in cm

P_a = annual rainfall in cm

m = coefficient depending on coefficient of variation 0.6 to 0.607 for C_v changing from 0.1 to 0.7.

ACTUAL SEDIMENTATION RATES IN INDIAN RESERVOIRS

SEDIMENTATION IN INDIAN RESERVOIRS

Soil erosion and consequent transportation of silt by streams is a natural phenomenon and is a function of soil and or rock strata, country slope, valley shape, natural vegetation and the management of the catchment. The reservoirs by themselves do not and have not accelerated the sedimentation rate. The effects of these projects on siltation, if at all, is nominal. On the other hand, these projects help in stabilizing and reducing river slopes (and thereby sediment carrying capacity of stream) and arresting soil erosion in more than one way. The project area which might have earlier been lying unattended, gets all the attention and is surveyed in this respect and the necessary soil conservation measures are carried out as part of the project. The creation of lake and its siltation helps, in most cases, in stabilizing the hill slopes.

Some people suggest comprehensive soil conservation measures as panacea to arrest and control soil erosion and thereby sedimentation of reservoirs. This is neither possible nor practical. Firstly the cost of treatment would be prohibitive (the present rate of catchment area treatment for Indus, Ganga and Brahmputra basins works out to about Rs. 12,540/- per ha which for Tehri project would mean an investment of over Rs. 900 crores at 1994 price level and if the work takes say 12 year time, the outrun cost would be about Rs. 3250 crores). Secondly the occurrence of big slides like Gohan slide, Bela Kuchi slide etc in these valleys are natural occurrence, which have not been caused by construction of any water resources project.

Thus, a practical and constructive approach in this respect would be to make a comprehensive catchment survey in respect of soil erosion, which is a phenomenon to be taken care of irrespective of the proposed projects in the area, and then evaluate the impact of a particular project. The result of this should be used as input for finalising remedial measures which will not only mitigate the impact due to the project but go a long way in improving the catchment as a whole.

One more aspect which has been overlooked is the diminishing silting rate noticed on some important reservoirs. That the Indian reservoirs would not be silted up in less than 100 years is substaintiated from observations charted in Table 5.1 and 5.2 which have served more than 50 years already and which have come up after Independence.

Table 5.1 Sedimentation Rate In Large Reservoirs Which Have Served More Than 50 years of their useful life (After A.K. Shangle WAPCOS Publication 1991)

Sl.	Name of reservoir	State	Storage capacity M m^3	Year of impounding	Year of last survey	Average rate of silting ha m/100 km^2/yr	Average annual loss of storage %
1.	Nizampur	A.P.	841.18	1930	1975	4.891	1.26
2.	Himayat Sagar	A.P.	107.79	1927	1976	4.467	0.52
3.	Mettur	T.N.	2708.76	1934	1984	2.520	
4.	Dhukwan	U.P.	105.45	1907	1980	0.304	0.61

Table 5.2 Sedimentation Rate in Large Reservoir Constructed After Independence

Sl.	Name of reservoir	State	Storage capacity M m^3	Year of impounding	Year of last survey	Average rate of silting ha m/100 km^2/yr	Average annual loss of storage %
1.	Bhakra	Punjab/H.P	9840.0	1958	1973	5.87	0.3
2.	Punchet	Bihar	1575.6	1956	1974	10.00	0.7
3.	Maithon	Bihar	1353.0	1955	1979	12.38	0.5
4.	Mayurakshi	W.B.	606.4	1955	1971	16.26	0.5
5.	Tunghbadra	Karnatak	3747.8	1953	1972	6.44	0.5
6.	Matatila	U.P.	982.5	1956	1974	3.82	0.9
7.	Hirakud	Orissa	8105.0	1957	1982	6.82	0.7
8.	Shivaji Sagar (Koyna)	Maharashtra	2979.0	1961	1971	15.04	0.8
9.	Gandhisagar	M.P.	7746.0	1960	1975	9.64	0.3
10.	Ramganga	U.P.	2442.6	1978	1987	negligible	

Sources - N.I.H.Publication 'Sediment Yield from Different Land Uses', 1986 C.B.I. & P Tech. Report No. 19, 1980 & C.B.I. & P Technical Report No. 20 Vol. I Sept. 1980 and Vol. II January 1981.

The deposition of sediment in different Indian Reservoir is shown in figure 5.1 for Bhakra reservoir, figure 5.2 for Panchet Hill reservoir; figure 5.3 for Shivajisagar (Koyna Dam), figure 5.5 for Mayurakshi reservoir (figure 5.4 shows particle size distribution of sediment load), figure 5.6 for Tunghbadra reservoirs and figure 5.7 gives longitudinal bed profiles of sedimented bed of Matatila reservoir. Figure 5.8 shows sediment deposits in different depth of Matatila reservoir.

C.W.C. (1991) have found that the analysis of capacity survey data of 43 reservoirs in India show a vide variability in sedimentation rates. The sedimentation rate is affected by multiple factors like hydrometeorology, physiography, climate etc. Considering these factors the whole country has been classified in 7 regions. The sedimentation rates in reservoirs region-wise are as given in Table 5.3 below.

Table 5.3
Region Wise Sedimentation Rate in Reservoirs

Sl.No.	Region	Sedimentation rate ha m/100 km^2/year
1.	Himalayan region (Indus, Ganga, Brahmputra region)	5.658 to 27.85
2.	Indo Gangetic Plateau	0.3 to 16.03
3.	East flowing rivers excluding Ganga upto Godavari	6.08 (Hirakud)
4.	Deccan Peninsular east-flowing rivers including Godavari	0.15 - 12.6
5.	West flowing rivers upto Narmada	-
6.	Narmada Tapti Basin	3.16 - 7.16
7.	West flowing rivers	0.96 - 25.4

REDUCTION IN SILTATION RATE WITH PASSAGE OF TIME

Dr. A.N. Khosla had observed that in reservoirs having small sluicing capacity with respect to normal floods and no reservoirs above them, the siltation rate is comparatively high in the first 15-20 years and there after falls off and may ultimately become negligible. This is because the obstruction by the dam causes the dips and the flanks of the storage basin to fill up with silt in early years. A stage comes when the river section is adjusted to carry the normal discharge and disposal of sediment load in the area of reservoir is harmonisd with the condition of flow. Besides the progressive development of deltas above reservoir helps in trapping of some of the silt load. Further shrinkage and settlement of deposited silt also takes place due to weathering action and superimposed loads of additional silt deposits. This results in reduction of silt volume thereby reducing the sedimentation rate. Experience on Indian reservoirs indicate that the sediment yield or erosion decreases after reservoir impoundment.

C.W.C. studied in detail four reservoir to determine the trends of siltation rate with passage of time. The reservoirs chosen were, Maithon and Panchet (both in Bihar), Matatila (in U.P.) and Bhakra (in Punjab and H.P.).The conclusion draw by CWC (ref. Compendium on Silting of Reservoirs in India, January 1991) is reproduced :

"The enveloping curves of these reservoirs show that the silting rate has been comparatively higher during first 15-20 years and thereafter has fallen significantly". The data in respect of these four reservoirs are : (Table 5.4)

Table 5.4 Reduction of Sedimentation Rate with Time - Indian Reservoirs

Reservoir	Sedimentation rate (ha m/100 km/yr)	
	At first survey	At last survey
Maithon	12.53	9.06
Panchet	12.13	3.36
Matatila	11.82	5.29
Bhakra	6.53	5.66

Statement 1 (3 sheets) adopted from CWC publication shows rate of silting in different reservoirs.

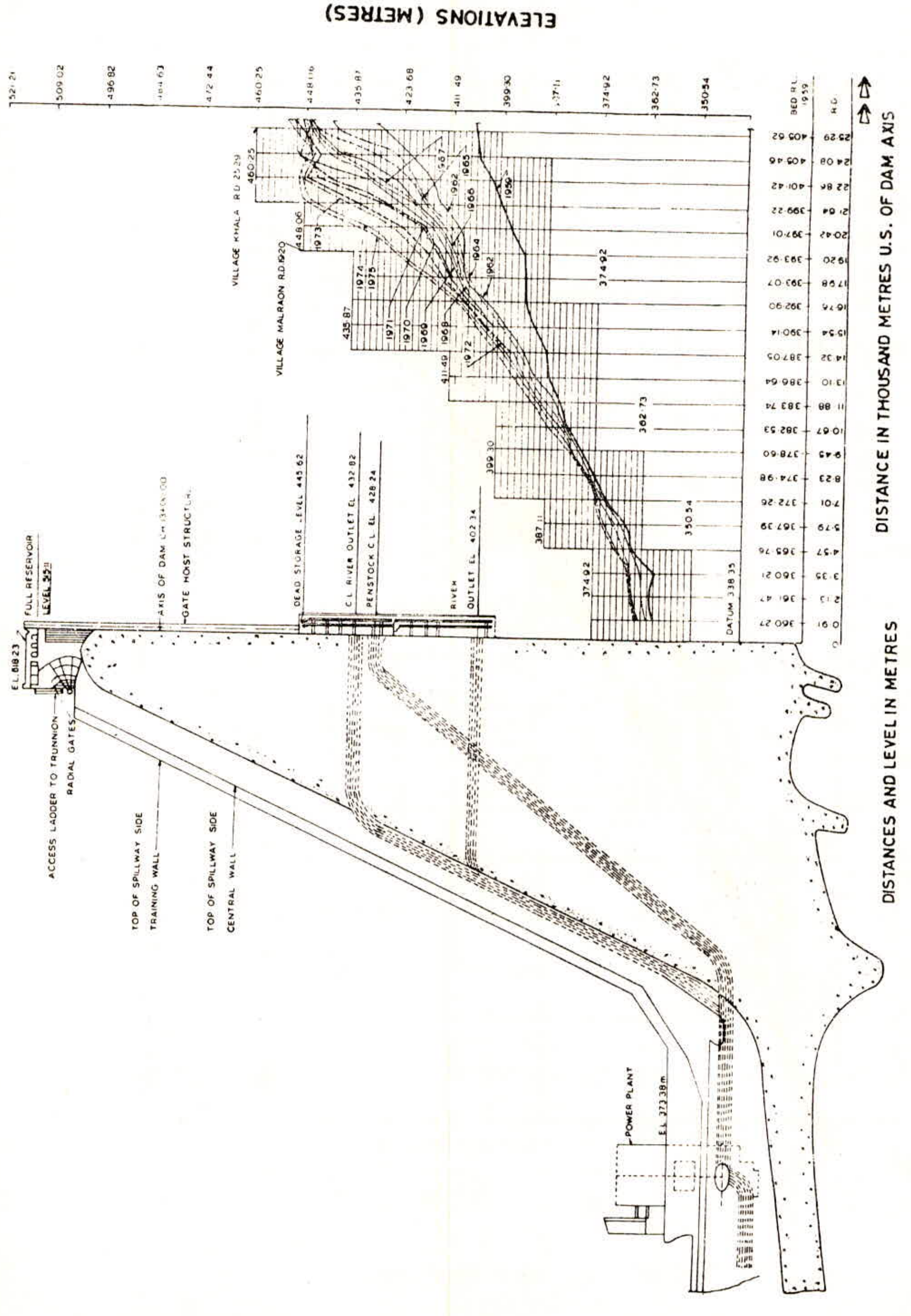


Figure 5.1 Longitudinal section of main channel showing yearly silt deposit

Reproduced from Fig. 5.4 on page 162 of C.B.I. & P. Technical Report No. 20, September 1980 "Sedimentation in Reservoirs" Vol. I

Reproduced from the Fig. 1.6 on page 27 of C.B.I. & P. Technical Report No. 20, September 1980 "Sedimentation Studies in Reservoirs" Vol. I

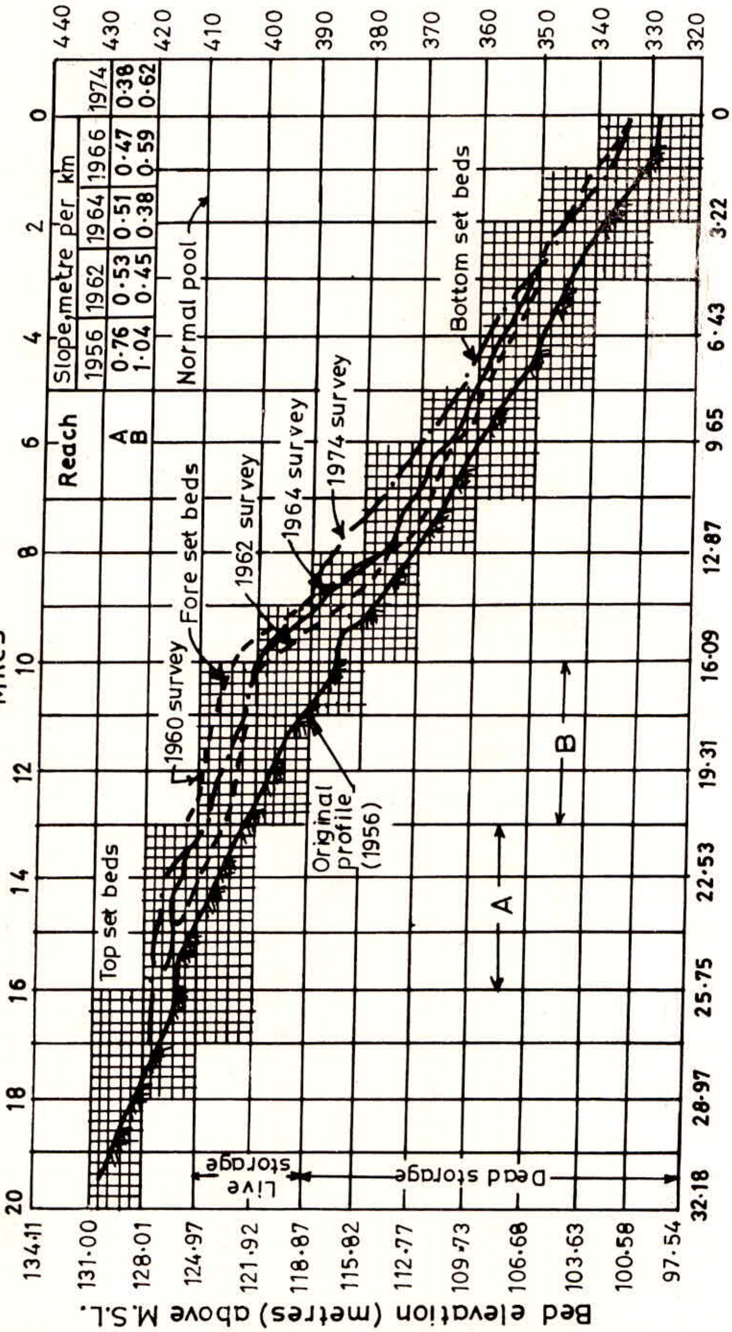


Figure 5.2 Longitudinal profile of reservoir bed (Panchet Hill Reservoir)

Reproduced from Fig. 4.10 on page 143 of C.B.I. & P. Technical Report No. 20, September 1980 "Sedimentation in Reservoirs" Vol. I

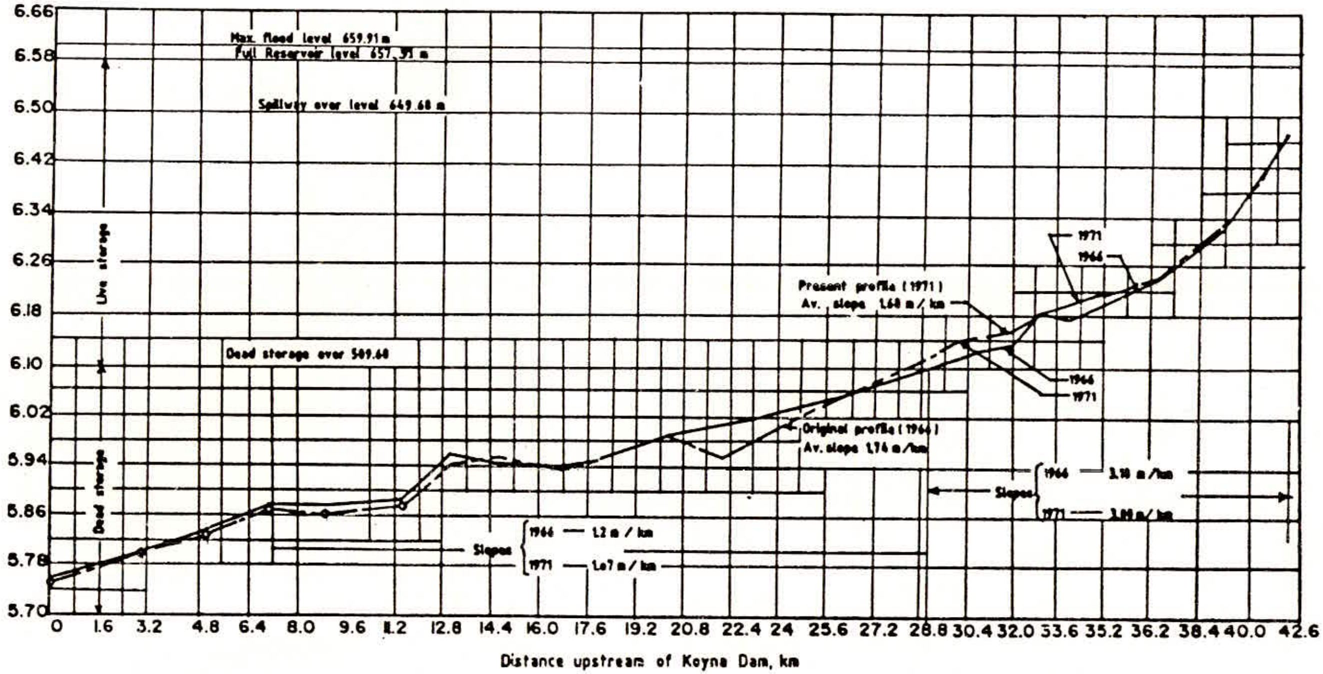


Figure 5.3 Profile of Reservoir Bottom

Reproduced from Figs 11 and 12 of C.B.I. & P. Technical Report No. 20, "Sedimentation Studies in Reservoirs" Vol. II Page 61 January 1981.

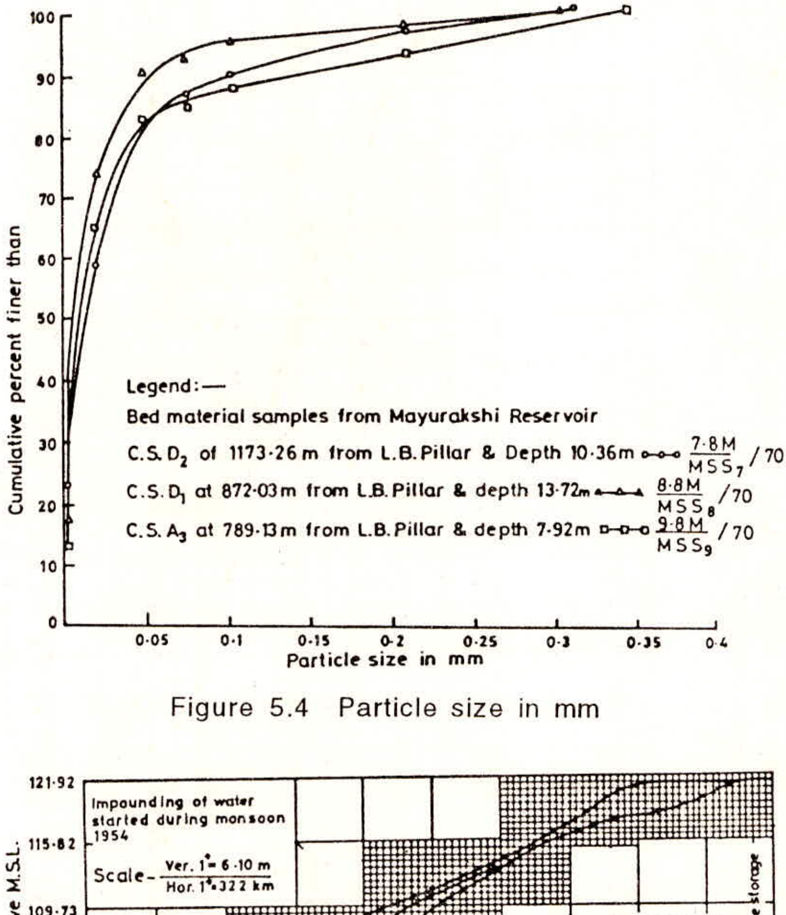


Figure 5.4 Particle size in mm

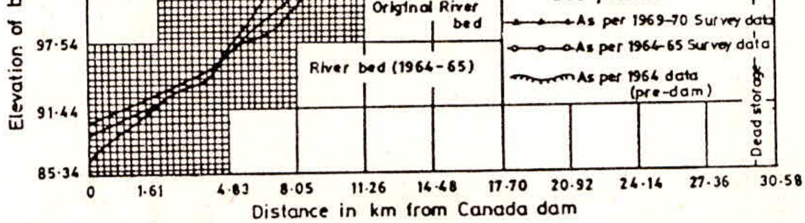


Figure 5.5 Longitudinal Section of River bed (1954-70)

Reproduced from Fig. 19 on page 153 of C.B.I. & P. Technical report No. 20, January 1981, "Sedimentation Studies in Reservoirs" Vol.II

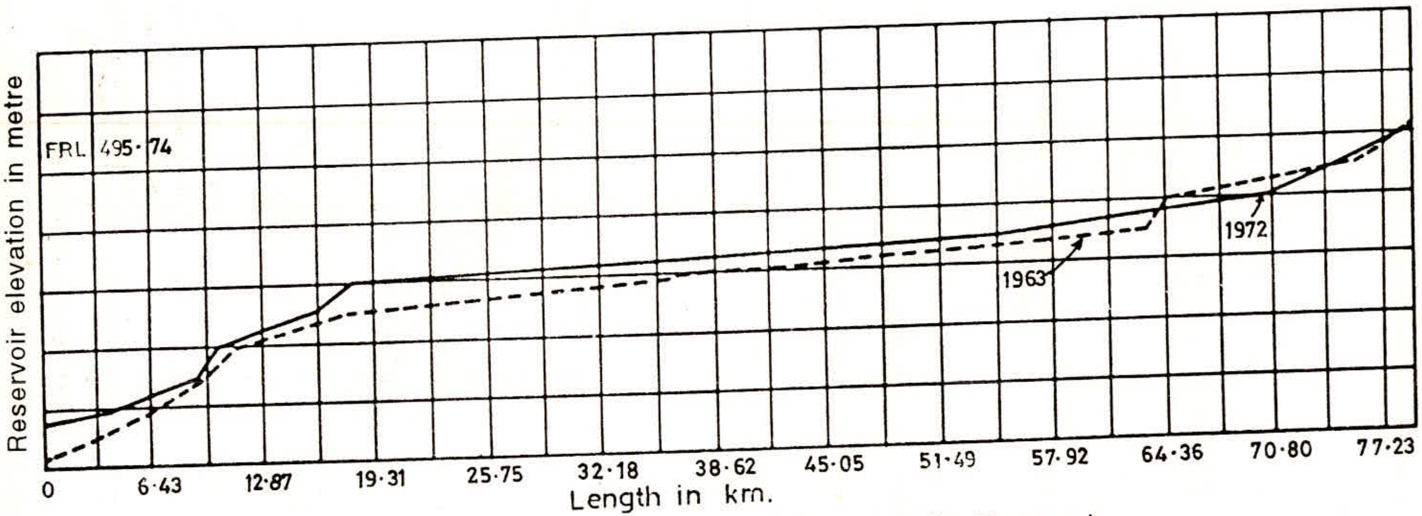


Figure 5.6 Longitudinal section of Tungabhadra Reservoir

Reproduced from Figs. 3.18 and 3.19 on page 117 of C.B.I. & P. Technical Report No.20 September 1980 "Sedimentation studies in reservoirs" Vol.I

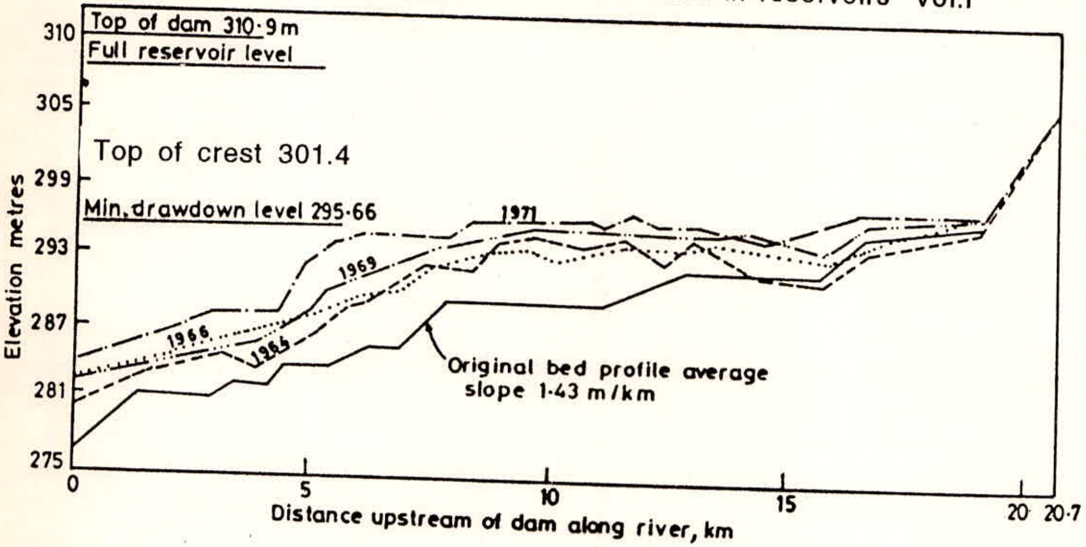


Figure 5.7 Longitudinal bed profile of Matatila Reservoir

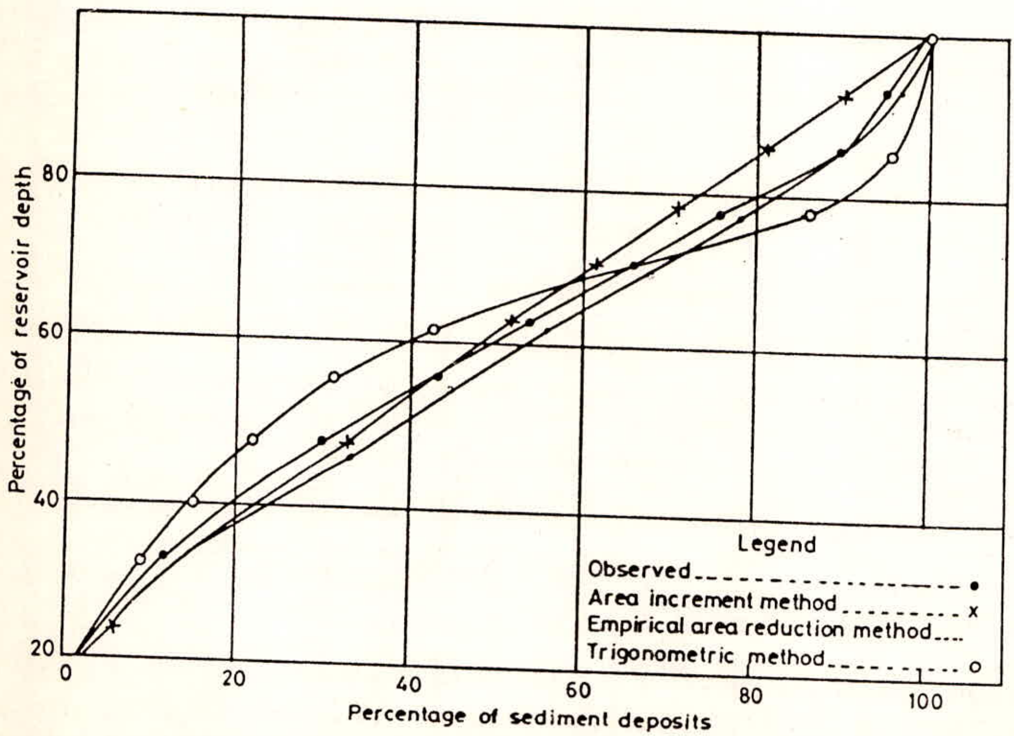


Figure 5.8 Showing depthwise distribution by various methods (Matatila)

DISTRIBUTION OF SEDIMENT IN RESERVOIRS

GENERAL

There was a time when it was believed that sediment always deposited in the bottom elevations of a reservoir rather than depositing throughout the full range of reservoir depth. It is now fully realized that sediment deposits spread throughout the reservoir reducing the incremental capacity at all elevations (Fig. 6.1).

Major design considerations due to sediment deposits include:

1. Elevation to which sediment will accumulate at the dam in a given period of time. This information is useful in deciding the elevation of the river outlet and power penstock skills.

2. Reduction of the live storage capacity: If this loss can be predicted, the structure height can be set to provide the required water supply storage.

3. Deposits of the sediment in the upper reaches of the reservoir: These deposits can result in a significant increase in the water surface elevations upstream.

4. Effect on recreational developments around the reservoir: The sediment deposits could influence the location of such facilities especially when the reservoir is one that will have considerable drawdown exposing sediment deposits.

5. Reservoir planned solely for sediment accumulation: A considerable portion of the total sediment stored may be above crest elevation of the reservoir.

It is therefore clear that estimating only the amount of sediment inflow to a reservoir is not sufficient. We must know where this sediment will deposit.

ASSOCIATIONS OF THE FLOOD PLAIN AND CHANNEL DEPOSITS, WHEN THERE IS NO RESERVOIR IN THE UPSTREAM OR WHEN THERE IS RESERVOIR.

In the normal flood-plain association of sediments, vertical accretion deposits cover coarser deposits of lateral acceleration and channel fill. The vertical-accretion deposits cover the flood plain with a fairly uniform thickness of fine sediments sloping away from the channel to the valley sides. The deposits of vertical accretion are the chief sources of the fertile bottom land in most valleys.

Modern channel-fill deposits occur in the present channel and in abandoned channels. In the latter case they may be covered by vertical accretion deposits. Sand splays occur immediately along side present or former channels and interfinger into

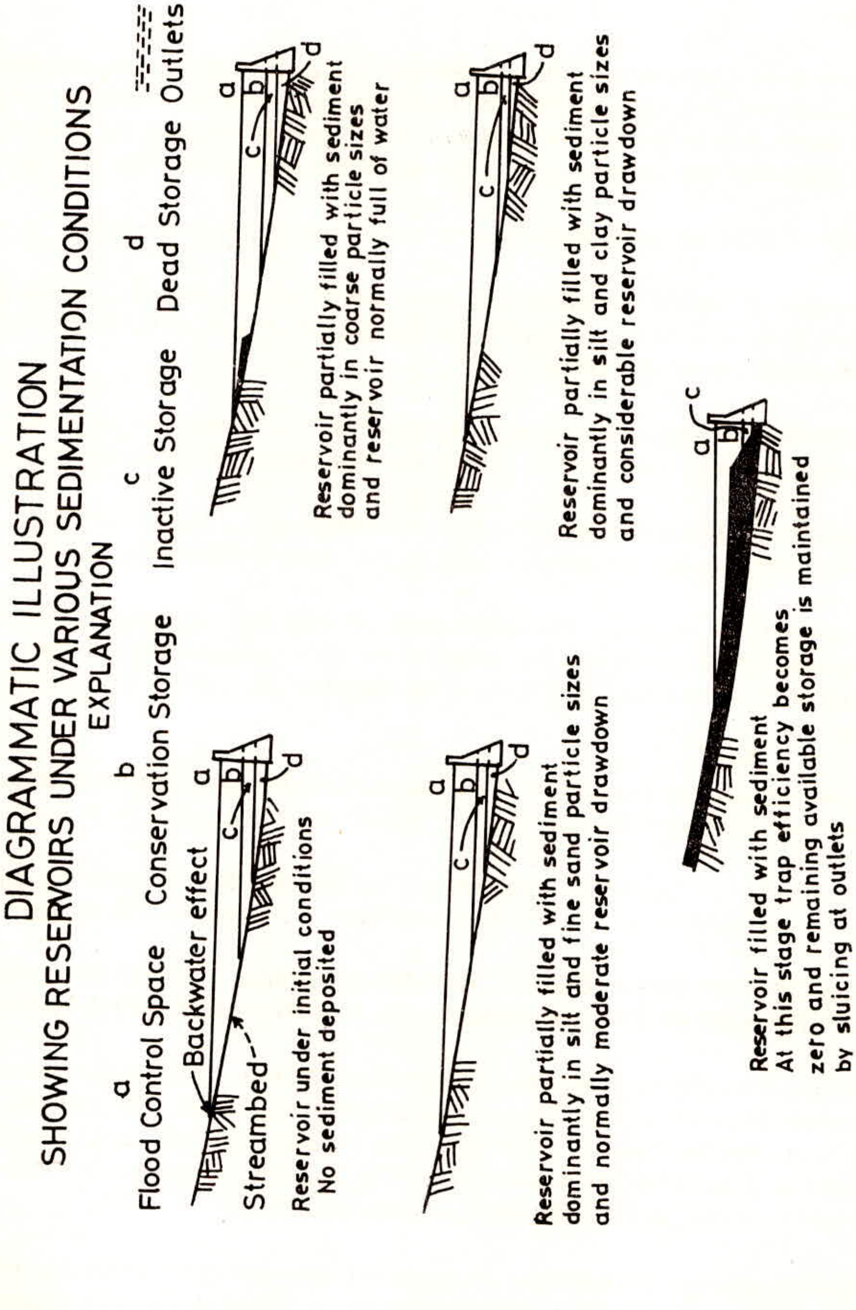

DIAGRAMMATIC ILLUSTRATION
SHOWING RESERVOIRS UNDER VARIOUS SEDIMENTATION CONDITIONS
EXPLANATION
a Flood Control Space
b Conservation Storage
c Inactive Storage
d Dead Storage
Outlets
Backwater effect
Streambed
Reservoir under initial conditions
No sediment deposited
Reservoir partially filled with sediment dominantly in coarse particle sizes and reservoir normally full of water
Reservoir partially filled with sediment dominantly in silt and fine sand particle sizes and normally moderate reservoir drawdown
Reservoir partially filled with sediment dominantly in silt and clay particle sizes and considerable reservoir drawdown
Reservoir filled with sediment
At this stage trap efficiency becomes zero and remaining available storage is maintained by sluicing at outlets

Figure 6.1

the vertical accretion deposits from the valley sides. The characteristically low area between the natural levels and the colluvial deposits is called the back swamp part of the flood plain. The characteristics of the different types of deposits in the normal flood plain association are summarised in Table 6.1.

Table 6.1 Characteris of Genetic Types of Valley Deposits

	Types of Deposits				
	Colluvial	Fluvial			
		Vertical accretion	Splays	Lateral	Channel fill accretion
Principal Origin	Concentration by slope wash and mass movements	Deposition of suspended load	Deposition of bed load	Deposition of bed load and always prominent, but suspended load may be dominant.	Deposition of bed load and suspended load
Usual place of deposit	At junction of flood plain and valley sides	On entire flood plain surface	On flood-plain surface adjacent to the stream channel.	Along side of channel especially on the inside of bends	Within the channel
Dominant texture	Varies from silty clay to boulders	Dominantly silt; often sandy, especially near channel often much clay	Usually sand; may be gravel or boulders	Sand or gravel; may include silt or boulders	Usually sand silt and gravel; may include silt or boulders
Relative distribu-tion in the valley fill	Interfinger with the fluvial deposits along outer margins of flood plain	Overlie deposits of lateral accretion and channel deposits overlain by or inter-bedded with splay and colluvial deposits; usually cover most plain surface	Form scattered lenticular deposits overlying or inter-bedded with vertical accretion deposits adjacent to present or former channels.	Usually overlain by vertical accretion deposits often under-lain by channel-fill deposits, may extend across entire flood plain width	Usually from elongate deposits of relatively small crosssection, winding through flood plain; may underlie vertical accretion deposits.

METHODS FOR PREDICTING SEDIMENT DISTRIBUTION

Two methods can be used for predicting the sedment distribution.

(i) The area Increment Method.
(ii) Empirical Area Reduction Method.

Both proceudre involve the adjustment of the original surface area to reflect the decrease in area with sedimentation (Fig. 6.2).

Area Increment Method:

This method was developed by E.A. Cristofano and is basically mathematical.

This is based on the assumption that the sediment deposition in a reservoir can be approximated by reducing the reservoir area at each reservoir elevation by a fixed amount. It is expressed as below:

$$V_s = A_o (H - h_o) + V_o \qquad 6.1$$

where

A_o = area correction factor in hectares which is the original reservoir area at the new zero elevation at the dam site.

V_o = sediment volume below new zero elevation (hectare metres)

V_s = sediment volume to be distributed in the reservoir (hectare-metres).

H = reservoir depth at the dam-stream, bed to maximum normal water surface (m)

h_o = depth in metres to which reservoir is completely filled with sediment-new zero elevation.

This equation states mathematically that the total volume of sediment Vs consists of the portion which is uniformly distributed vertically over the height $H-h_o$ plus the portion below the new zero elevation of the reservoir.

Design Example - Use of Area-Increment Method - after R.S. Varshney

The computations for probable sedimentation in Lakhwar reservoir are given in Table 6.2. The table shows the distribution of sediment volume of 248 M m^3. The new zero elevation at the dam works out to 697 m.

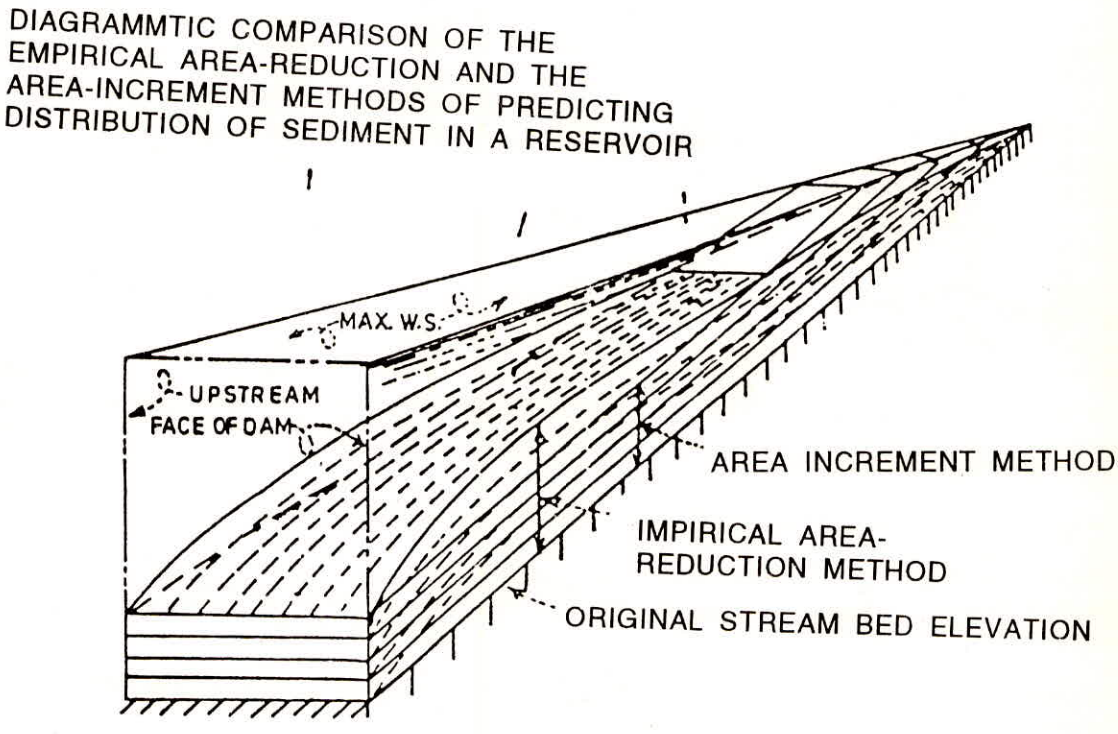


Figure 6.2 Diagrammatic comparison of the empirical area-reduction and the Area-Increment methods of Predicting distribution of sediment in a Reservoir

TABLE 6.2 LAKHWAR RESERVOIR-SEDIMENT DEPOSITION COMPUTATIONS (Area Increment Method)

Stream bed elevation	=	623.00 m
Max normal water surface elevation	=	796.00 m
Total sediment	=	247.00 M m^3

Elevation (metres)	Original area (hectares)	Original capacity M m^3	A_0 hectares	Sediment Volume M m^3	Revised Area hectares	Revised Capacity M m^3
796.00	965	580	195	248	770	332
792.68	930	550	195	242	735	308
777.44	772.5	415	195	206.5	577.5	208.5
762.20	625	305	195	182	430	123
746.96	500	220	195	154	305	66
731.72	394	157.5	195	123.7	199	33.8
716.48	300	105	195	92.85	105	12.15
701.25	215	65	195	63.21	20	1.79
697.00	195	55	195	55	0	0
686.00	147.5	35	147.5	35	0	0
670.75	95	12.5	95	12.5	0	0
655.52	60	5	60	6	0	0
640.21	22.5	3	22.5	3	0	0
625.04	2.45	0.2	2.45	0.2	0	0
623.00	0.00	0.0	0.00	0.00	0	0

The steps are briefly given below:

Step-1 From the equation 6.1, h_0 can be obtained by trial and error.

Step-2 Compute accumulative sediment volume by applying the area correction factor at each depth increment (col 4) and computing volumes by average end-area formula. Computed volume should check the predetermined sediment volume preferably within 1 percent.

Step-3 Reduce original area at each increment by the area correction factor to give revised area table (col. 6 = col.2 - col.4)

Step-4 Determine the revised capacity table by reducing the original capacity at each increment by the sediment accumulation (Col. 7 = Col. 3 - Col.5).

The results are compared with the original curves (Fig. 6.3)

Basic Data

V_s = 247 M m^3 (sediment volume)

H = (795-623) = 173 m.

V_o, H_o, A_o are obtained by assuming h_o and reading V_o and A_o from original area capacity curves.

Basic equation $V_s = A_o(H-h_o)+V_o$

By trial and error.

h_o	=	(697 - 623) = 74 m (zero elevation 697 m)
A_o	=	195 hectares
V	=	55 x 10^2 hectare -metre. 55 million cubic metres

$A_o (H-h_o) + V_o$ =195 (796-623) - 74) + 55x10^2
= (195x99) +5500 hectares m
= (195x0.99+55) M m^3
= (193+55) = 248 M m^3
= 248 million cubic metres

This is nearly equal to 247 M m^3. (The difference should not be greater than 1%). Thus area correction factor is 195 and new zero elevation = 697 metres.

Column Details

1,2,3. Basic data.

4. Area correction factor as determined. above.

5. Sediment volume as determined from equation $V_s = A_o(H-h_o)+V_o$ for different values of H, based on above A_o, h_o,V_o

6. Revised area obtained by substracting col. 4 from col. 2
7. Revised capacity obtained by substituting col. 5 from col. 3.

The results are exhibited in Figure 6.3.

Empirical Area Reduction Method.

This is a mathematical procedure developed on the basis of actual occurrences in large reservoirs.

Whitney M. Borland and Carl L. Miller have classified the reservoirs into four standard types on the basis of analysis of 30 reservoirs in U.S.A.

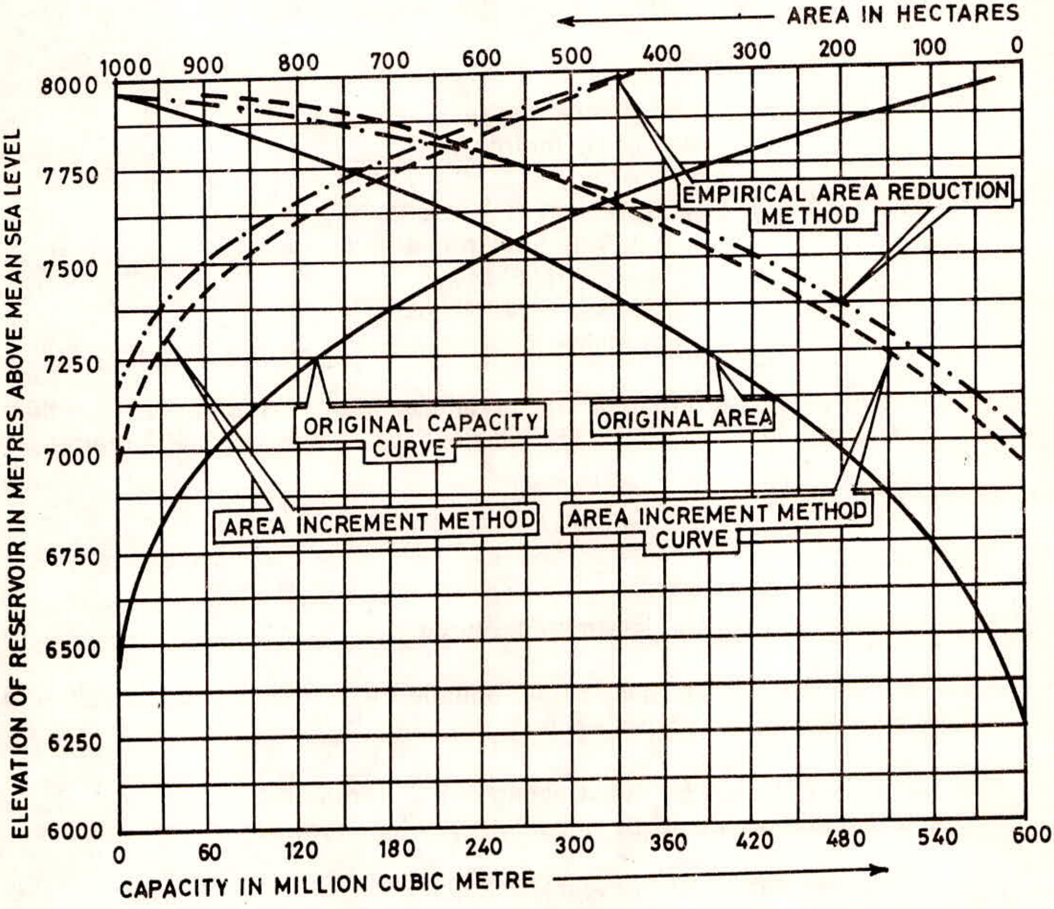


Figure 6.3 Original and revised area capacity curves Lakhwar reservoir

"M" is the reciprocal of the slope of the line obtained by plotting reservoir depth as ordinate against reservoir capacity as abscissa on log-log paper (Fig 6.4 and 6.5)

The general classification resulting from the analysis of the data is shown in Table 6.3

Table 6.3 GENERAL CLASSIFICATION OF DATA - after Borland and Miller

Reservoir type	Standard Classification	Value of m
Lake	I	3.5 -4.5
Flood plain-foot hill	II	2.5 -3.5
Hill	III	1.5 -2.5
Gorge	IV	1.0 -1.5

The 4 standard type sediment deposit versus depth curves have been converted to area design curves by Borland and Miller for use in the computation (Fig 6.6). The conversion from the standard type sediment deposit curves to the area design curves has been made by W.T. Moody by applying the equation.

$$A_p = Cp^m (1-p)^n \qquad 6.2$$

where

A_p = a dimensionless relative area at relative distance p above stream bed.

c, m, n = dimensionless constants which are determined by the type of reservoir.

Numerical values of m and n were computed by Borland and Miller by trial and error using a least square procedure so as to make the analytical curve the best possible fit to the flood survey data. With m and n determined, C is fixed by consideration that the total area under the A_p curve must equal unity. The characteristic constant C, m and n determined for the 4 types of reservoirs are given in Table 6.4. J.M. Lara (1962) revised these coefficients which are also given in Table 6.4.

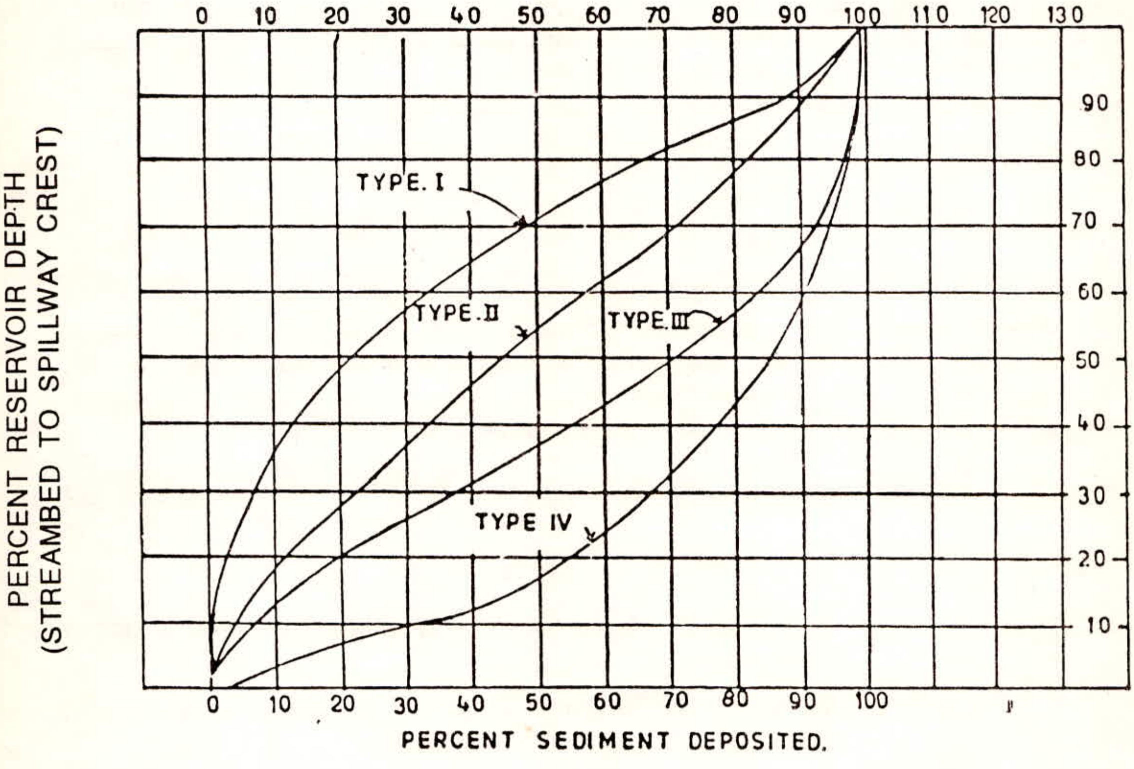
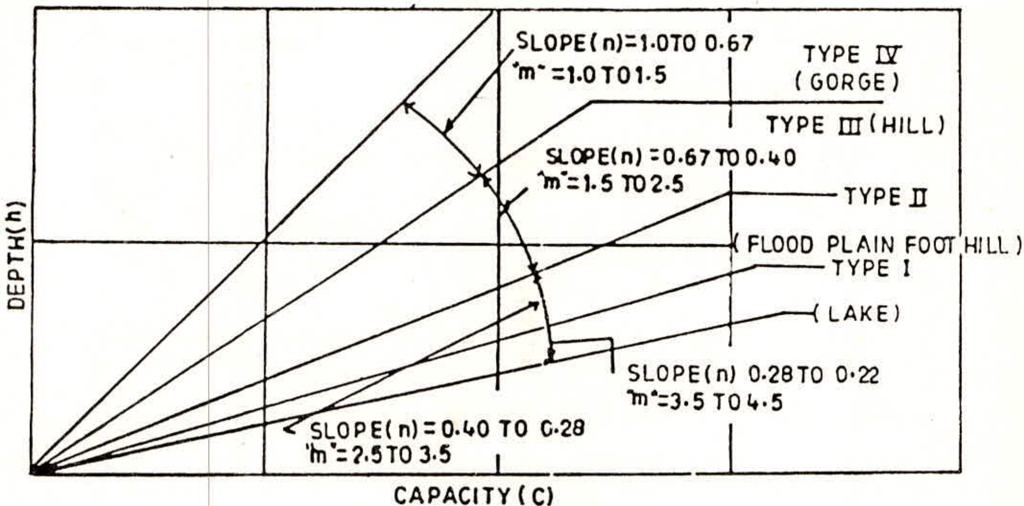


Figure 6.4 Type curves of percent sediment deposited vs percent reservoir depth based on actual occurrence



CLASSIFICATION OF RESERVOIRS
BY
DEPTH VERSUS CAPACITY
RELATIONSHIP

Figure 6.5 Classification of Reservoir by depth versus capacity Relationship

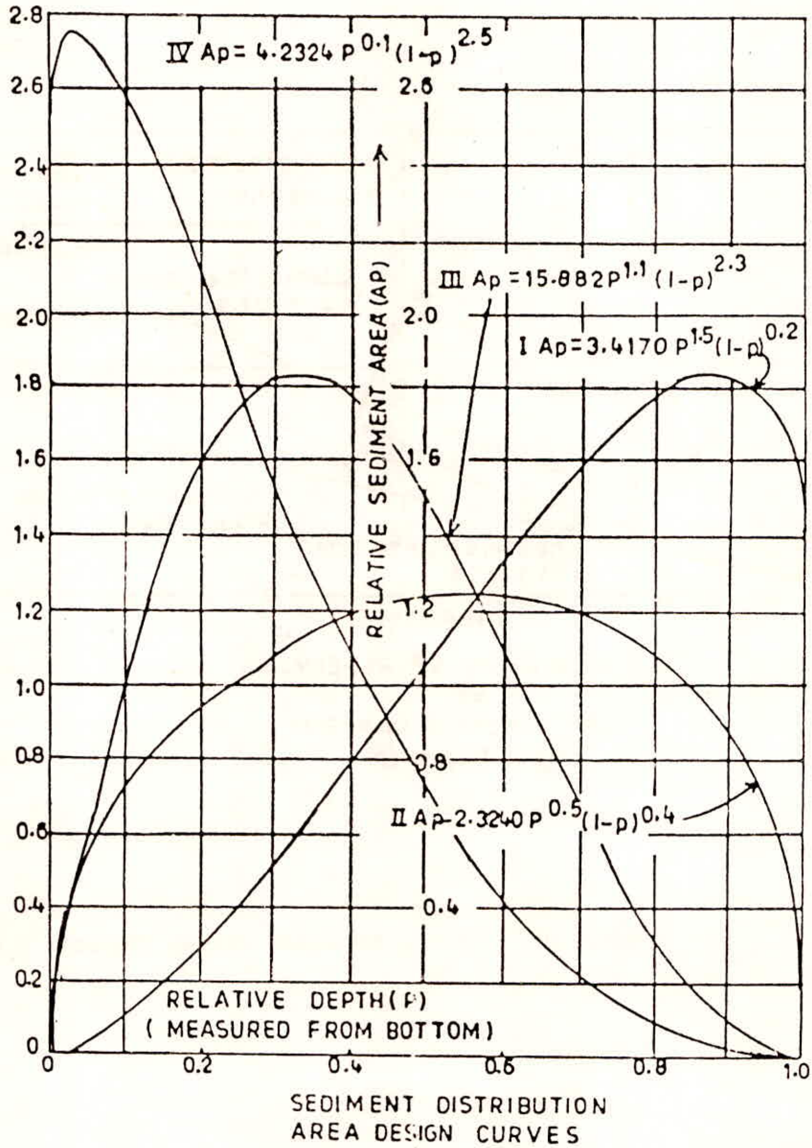


Figure 6.6 Sediment distribution area design curves (Based on storage curves- After borland & Miller

Table 6.4 Characteristics for 4 Standard Type Reservoirs-Lara's Values Given in Parentheses

Type	C	m	n	Sediment storage near
I	3.4170 (5.074)	1.5 (1.85)	0.2 (0.36)	Top
II	2.3250 (2.487)	0.5 (0.57)	0.4 (0.41)	Upper middle
III	15.8820 (16.967)	1.1 (-1.15)	2.3 (2.32)	Lower middle
IV	4.2324 (1.486)	0.1 (-0.25)	2.5 (1.34)	Bottom

The procedure can be defined in tabular form as below:

Step 1 Determine the relative depth for each increment at the dam (Col.4). This is merely the ratio of the incremental depth to the total depth. This is determined from values in Col. 1.

Step 2 Determine values of relative sediment area (A_p) from the standard type curve selected (Fig. 6.4 and 6.6). Enter the curve with relative depth for each increment and red corresponding A_p values (Col. 5).

Step 3 Select a first approximation of the probable sediment elevation at the dam after sedimentation. Areas at and below this elevation will equal areas in Col. 2. Sediment areas for each depth increment above the estimated new zero elevation are obtained by dividing the original area at zero elevation (Col. 2) by the corresponding A_p values (Col. 5) and multiplying this ratio K by the A_p value at each succeeding increment.

Step 4 With the sediment areas established (Col. 6), the incremental sediment volumes can be computed by the average end area formula and entered in columns 7. Columns 6 and 7 represent the first approximation. If the sediment volume summation in Col. 7 exceeds or is less than that desired, a second approximation is made. Second and third approximations are shown in Columns 8 to 11.

Step 5 Accumulate the sediment volumes shown in Col. 11 and enter in Col. 12.

Step 6 Determine the revised areas for after sedimentation (Col. 13 = Col.2-Col.10).

Step 7 Determine the revised capacities (Col. 14 = Col. 3-Col.12).

Usually 2 or 3 trials are required to obtain the desired balance. If the summed volume is within 1% of the predetermined volume, sufficient accuracy has been attained.

The calculations for the earlier Design Example of Lakhwar dam by this method are given in Table 6.5 (after R.S. Varshney).

Assume new zero elevation	=	702.74 m
Area	=	225 hectares
Ap	=	1.24
K	=	181

Column Description

1, 2, 3. Basic data
4. Depth
5. Relative depth = $\frac{\text{depth}}{\text{total depth}}$
6. Ap, value obtained from graph for standard type of curve (Type II for Lakhwar).
7. Zero elevation is found by trial and error.
8 & 9 Explained in Table.
10. Col.2-Col.7.
13. Col.3-Col.10.

Table 6.5 shows the computation of distribution of 247 million cubic metres sediments in Lakhwar reservoir by this method. The new zero elevation at the dam works out to 702.74 m.

Area and capacity curves of Lakhwar reservoir before and after sedimentation are shown in Figure 6.3. A perusal of the curves indicates close agreement in the result by two methods.

ACTUAL SEDIMENT DISTRIBUTION IN DIFFERENT RESERVOIRS

Analytical as well as actual surveys have been made showing the deposit and distribution of sediment load in reservoirs. These are briefly discussed herein.

Silting in Lake Mead (Hoover dam or the Colorado dam in U.S.A.)

Tremendous quantities of materials have been removed from the channel below Hoover dam (Lake Mead). It has been found that 116,000,000 m^3 have been removed from the channel for a distance of 147 km below the dam during the silting in Lake mead.

Figure 6.7 shows the pattern of silting in Lake mead.

Reservoir Sedimentation in Other Dams of U.S.A.

Fig. 6.8 shows the location of sedimentation in 24 reservoirs in U.S.A. Each group of curves exhibits similar deposit characteristics and bring out the important fact that 50% of the sediment deposit lie in the upper half of the reservoir. This deposit generally encroaches upon the live storage whereas, in the part nearer to the dam, a large proportion of the dead storage, which is meant for deposits, may not be utilised. In the Fig. 6.8 Group A is Type I (Lake); B is type II (Flood plain-foot hill); C is Type III (Hill) and group D is Type IV (Gorge) reservoir classification after Borland and Miller.

Tarbela Dam Reservoir Sedimentation (analytical studies)

P.C. Chao and S. Ahmed (1985) developed mathematical models to estimate the sedimentation in Tarbela reservoir, Pakistan, on the basis of sediment load in Indus river. The reservoir capacity is 13.94 km^3 ($11.3x10^6$ ac ft) including 2.59 km^3 ($2.1x10^6$ ac ft) dead storage below E1. 396 m (1300 ft). The sediment model was calibrated by comparing the computed sedimentation profiles for the years 1979 and 1980 with the corresponding period surveyed delta profiles. The calibrated model was then verified with the 1982 field survey data.

Based on the deposited sediment volume computed by the model, the remaining reservoir capacity in each year was computed as shown in Fig. 6.9. It would be seen that in the year 2010 the reservoir will lose about 24 p.c. of its original capacity in 1974.

Sedimentation in Indian Reservoirs

The sediment deposit patterns in Bhakra, Panchet Hill, Maithon, Koyna, Mayurakshi, Tungbhadra and Matatila reservoirs are shown in Figures 5.1 to 5.9 in Chapter 5.

The observed distribution patterns of sediment for Mayurakshi, Matatila, Bhakra, Maithon, Panchet and Nizamsagar reservoirs are shown in Figure 6.10.

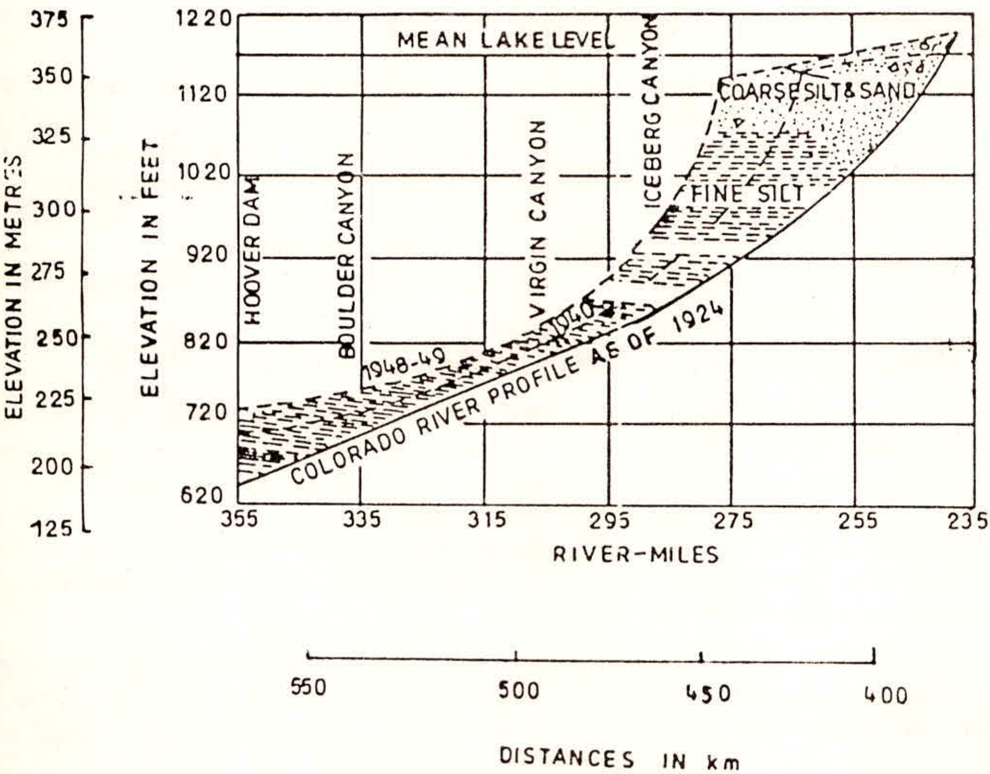
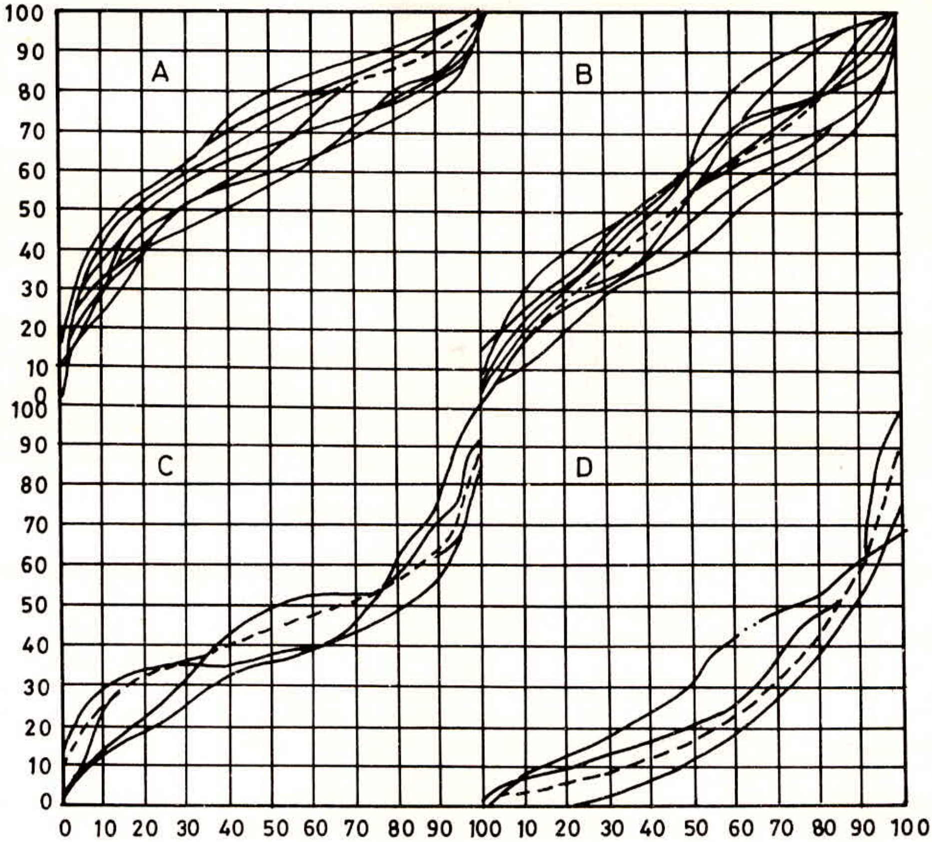


Figure 6.7 Showing deposits in Lake mead, determined by soundings in 1940 and 1948-49



Group A	Group B	Group C	Group D
1. Lake corpus Christi	1. Little Rock	1. Exchequer	1. Magalla
2. Cucharas	2. Mc Millan	2. San Carlos	2. John Martin
3. Guernsey	3. Roosevelt	3. Bullards Bar	3. Bartlett
4. Elephant Butte	4. Stony Gorge	4. Arrowrock	
5. Comble	5. Alamagordo		
6. Baffalo Bill	6. Santa Anita		
7. Conchas	7. Altus		
8. Lake Cheesman	8. Tongue River		
9. Altus			

Note:- Dotted lines show mean location of deposit.

Fig 6.8 : Showing location of sediment deposits in reservoirs in U.S.A. Ordinate : Percentage of reservoir depth. Abseissa : Percentage of sediment deposit (Dotted lines show mean location of deposit).

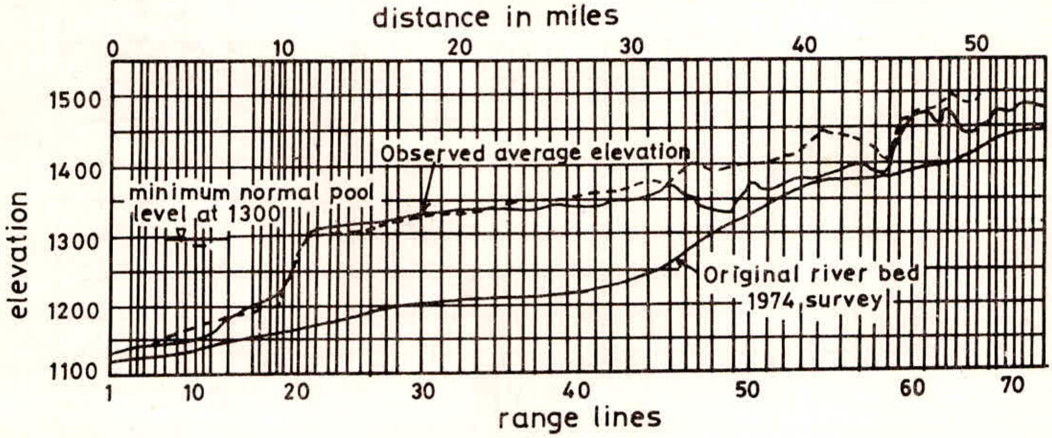


Figure 6.9a Calibration of mathematical model computed and observed average bed profiles 1982

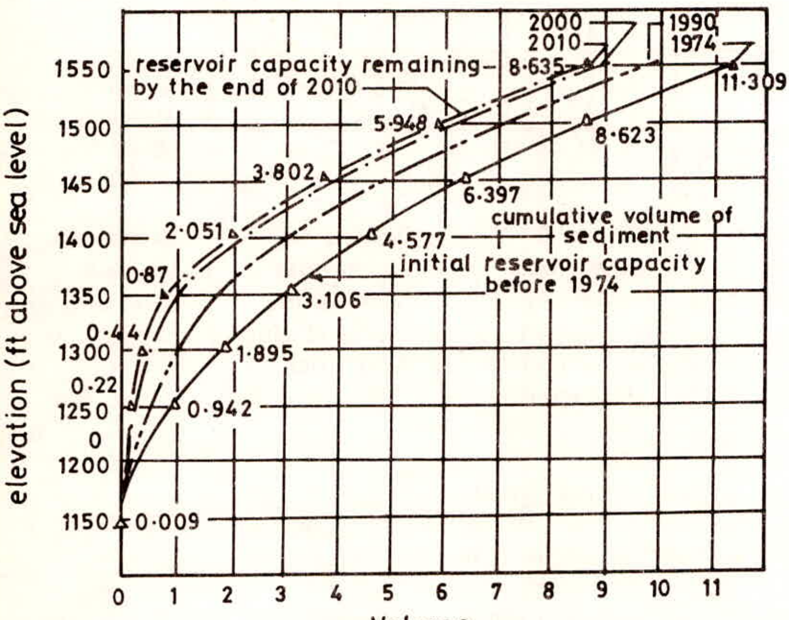


Figure 6.9b Cumulative volume of sediment
(MAF-10^6 acre ft. 1.2335 km^3 x 10^{-6} acre/ft)

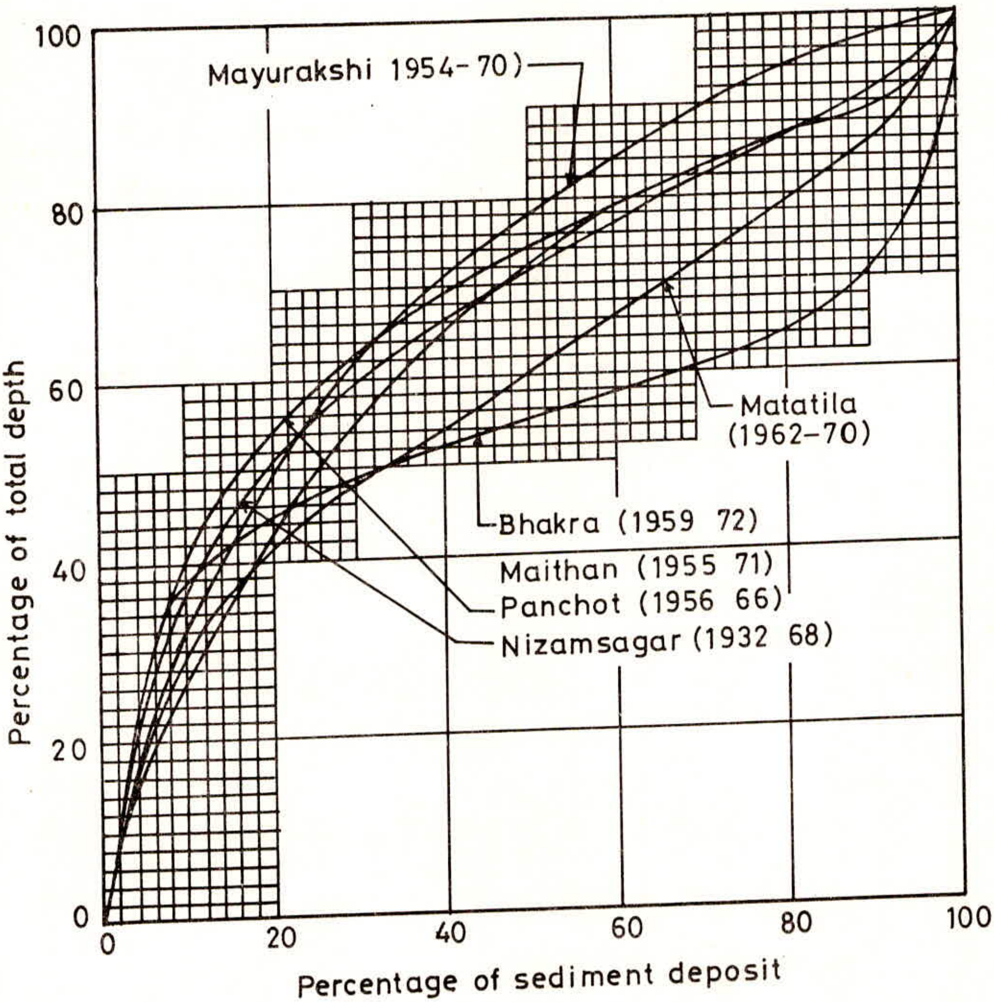


Figure 6.10 Distribution of sediment in different reservoirs in the country

Table 6.5 Sediments Deposition (Empirical Area Reduction Method)

Stream bed elevation = 623.00 m
Maximum normal water surface-elevation = 796.00 m
Total sediment = 247 M m2

Elevation Revised revised (metres)	Original Modified area (Hectares)M.m2	Original capacity (metres)	Depth depth	Relative II	Ap Type (K Ap)	Sediment area K=181	volume (A1+A2) H/2	Sediment Sediment volume (H.m.)	volume (H.m.)	Acc Sediment volume (M.m2)	Acc. (Col. 2-capacity (M.m=2)	Modified Acc. area Col.
1	2	3	4	5	6	7	8	9	10	11	12	13
796.00	965	580	173	1.00	0	0	141	24911.5	249.11	249.11	965	330.89
792.68	930	550	169.68	0.98	0.47	851	1925	24770.5	247.70	247.70	845	302.30
777.44	772	415	154.44	0.893	0.92	1167.5	3170	20045.5	228.45	228.45	605	186.55
762.20	625	305	139.20	0.805	1.07	199.5	3170	20045.5	200.45	20045.5	425.5	104.55
746.96	500	220	123.96	0.712	1.19	216	3360	16875.5	168.76	168.76	284	51.24
731.72	394	175.5	108.72	0.629	1.24	225	3460	13515.5	135.16	147.50	169	10.00
716.48	300	105	93.48	0.541	1.26	229.4	3120	10055.5	100.56	105	70.6	0
702.27	225	67.5	79.74	0.459	1.24	225	328	6936.5	69.36	67.5	0	0
701.25	215	65	78.25	0.455	1.24	215	2760	6607.6	66.08	65	0	0
686.00	147.5	35	63.03	0.366	1.14	147.5	1845	3847	38.47	35	0	0
670.76	95	12.5	47.76	0.276	1.07	95	1180	2002.5	20.03	12.5	0	0
655.52	50	5	32.52	0.188	0.94	60	630	822.5	8.23	5	0	0
640.28	22.5	3	17.28	0.0995	0.70	22.5	190-	192.5	1.93	3.6	0	0
625.04	2.45	0.2	2.04	0.0116	0.12	245	2.50	2.5	0.025	0.2	0	0
623.00	0.00	0.00	0.00	0.0000	0.00	0.00	0.00	0.0	0.000	0.0	0	0

Note: The sediment accumulation is coming more than the original capacity. To adjust it we have shifted the volume to higher elevation to be adjusted there. Hence, modified revised capacity.

LIFE OF RESERVOIRS

DIFFERENT ASPECTS OF LIFE OF RESERVOIRS

It has been the practice in the engineering profession to think of 'the useful life of reservoirs', only in terms of length of life. This concept is probably based on the business practice where a particular given asset is assumed to wear out or become obsolete within a given definite period of time. In this case, we should not see so much with the length of life of the reservoir but we have to think how long the reservoir has been useful to the community.

Normally, one would be interested to know when the capacity of a given reservoir would be fully depleted. But from the operational considerations, we have to assess when the sediment begins to encroach to the dependable storage preventing the reservoir from putting up its guranteed performance. The dependable storage capacity of reservoir is that part of the useful capacity which is needed during the period of sustained low flow to off-set consumption requirements, seepage and evaporation losses. This minimum requirement is necessary as safety factor to furnish the services during the driest periods of deficient rainfall and low run-off. The useful capacity varies from region to region depending upon the sediment content of the inflow, the size of the inflow, the size of the reservoir, operation schedule, and the type and the purpose for which the reservoir is built. In many cases, the useful capacity of the reservoir is found to vary from 50 to 80 percent of the original total capacity. When the reservoir capacity is depleted by silting, the reservoir will no longer have the capacity to serve the primary purpose for which it was built and as such we have to think of replacement.

But even after this period it may be left with storage capacity of considerable economic value. It may then be able to serve a lesser commanded area or generate lesser amount of energy but still remain economically efficient. It may then be put to use by itself or in conjunction with other systems, but when all feasible methods of utilizing the reservoir prove economically inefficient, it may be viewed as totally useless.

In case of flood control reservoir the picture would be different. Flood control, however, is often provided by gate control detention storage being the pool level maintained for power, irrigation water supply, etc. In such reservoirs flood control may not be seriously affected until the storage capacity at these levels is greatly affected by silting. Some reservoirs which are mainly constructed for flood control provided with large outlets at the base of the dam, pass the flood water at normal stream discharge velocities hence much of the sediment load may pass through and out of the basin. All this, leads us to the understanding of the various concepts of life of reservoir and the definitions of 'life' as accepted and understood by the majority.

(i) Useful Life: It is usually taken the period through which the capacity occupied by sediment does not prevent the reservoir from serving its intended primary purposes. It is said to have terminated when another reservoir has to be built to assist it to meet the inescapable commitments.

(ii) Economic Life: This is determined by the point in time when the effect of various factors such as physical depreciation by sedimentation, etc., obsolescence, changing requirements for project services and time discount and allowance for risks and uncertainty causes the costs of operating the reservoir to exceed the additional benefits to be expected from its continuation or in other terms during which period it can be operated with economic efficiency.

(iii) Usable Life: The reservoir can continue to serve some of the purposes though to limited extent even after expiry of its economic life, single or in conjunction with additional facilities created fro the purpose.

(iv) Design Life: This is either useful life or shorter of the expected economic life or fixed span of life 50/100 years (according to the practice of the agency owning the project) keeping in view various criteria, which period is adopted for economic analysis.

(v) Full Life : It is the number of years required for the reservoir capability to be fully depleted by sedimentation.

REVIEW OF RESERVOIR PERFORMANCE AND ECONOMIC LIFE

As is well understood, sedimentation in many reservoirs is encroaching on the live storage gradually reducing the capacity, and in course of time it may interfere with the operation making it uneconomic. It is, therefore, necessary to make an economic review of each project during the years of operation and particularly in those projects where sedimentation rate has proved much higher than what was estimated earlier at the time of project design. Such a review is necessary to ascertain the period when the project may prove economically inefficient. Further, such studies are also required for ascertaining the need for change in the system operation and the interest of future overall project planning of the country.

Economic life analysis involves in the comparison of the present value of the net costs and the present value of the net benefits in respect of the reservoir calculated for the entire period under consideration and brought down to the present level by applying a specified rate of interest. While computing the economic life, it would be necessary to consider appropriate hydrological inputs and demands to arrive at the expected values of the benefit streams, the damages, maintenance cost, etc. The cost of obsolescence may be incorporated by introducing a reduction factor in the benefit streams which may result on account of a reduced use of the system because of the availability of a more efficient alternative system developed in the future.

In benefit-cost study, the benefits and costs are expressed in monetary terms, and all the benefits and costs are converted to equivalent average annual accounts for selected period of analysis. The application of this procedure will necessitate consideration of the resource development policies of the country.

Formally the criterion for economic effectiveness may be taken as a benefit-cost ratio of unity which means that for the period of economic life the present value of net benefits will equal the present value of net cost at a specified rate of return.

In case of multipurpose projects, the benefit-cost ratio for different periods may be worked out for the entire project to ascertain the economic efficiency. In order to judge whether any of the particular functions of the reservoir is interfered with rendering the reservoir economically inefficient, the benefit-cost ratio needs to be worked out on the basis of apportioned cost to different purposes. This may indicate whether any modification in the system characteristics would yield any economic advantage.

With the available water storage as worked out for the various periods say 25, 50 75, 100 and 125 years, the benefit-cost ratio may be worked out and when this ratio falls below unity that period may be termed as the 'Economic Life' of the reservoir.

The dead storage provided in reservoir capacity is allowed for sedimentation. Actually all the sediment load does not go in dead storage. It encroaches upon live storage also. The encroachment and its distribution depends upon may factors such as reservoir operation, valley characteristics, capacity inflow ratio, sediment content in the inflow etc. `The Useful Life' of a reservoir is taken till its capacity is reduced to about 20% of the designed capacity.

The rate of sedimentation is higher in the initial stage and it decreases with years. This is due to fall in the trap efficiency of the reservoirs, consolidation and shrinkage of deposits and formation of delta.

The following data may be used as a guide to evaluate trap efficiency of a medium size reservoir. The annual loss of reservoir capacity as actually observed on Indian reservoirs is given in Table 7.1 (Data analysed by R.S. Varshney).

Table 7.1 Trap Efficiency

Capacity/Inflow (%)	Trap Efficiency	Annual Loss of reservoir capacity %
1	45	
10	87	
20	93	3.0
50	97	0.5
100	98	0.14
200	98.3	0.035
500	98.3	

EVALUATION OF USEFUL LIFE OF RESERVOIR

The useful life of reservoir has been calculated/estimated by different researchers. Relations and methodology have been given by them encompassing the reservoirs studied by them. Some of these are discussed herein.

Empirical Relations

Jiang (1980) Formula

An empirical formula has been derived to estimate loss of reservoir capacity, based on data of Chinese reservoirs.

$$R_s = 0.0002\, G^{0.95} (F/V)^{0.8} \qquad 7.1$$

where

R_s = average rate of loss of reservoir capacity per year %

G = average soil erosion modulus in the basin tonne/km^2/year.

F = drainage area, m^2

V = reservoir capacity, m^3

T.V. Taylor's Method (1930s)

T.V Taylor of the University of Texas has given a method to correlate reservoir capacities at different time intervals.

$$V_n = V_o R^n \qquad 7.2$$

where

V_n = reservoir capacity after n years.

V_o = capacity of reservoir before impounding

R = ratio of reservoir capacity at the end of one year to that of the capacity of the previous year, assumed to be constant, e.g. if capacity in the beginning is known and capacity after say 10 years is known then.

$$R^{10} = V_{10}/V_0$$

; R can be calculated.

Hence mean rate of silting per year = (1-R) x 100% 7.3

A. Rooseboom's relation (1975)

Rooseboom, on the basis of studies on five South African reservoirs and four U.S.A. reservoirs, has given the expression.

$$V_t/V_{50} = 0.376 \quad \ln\ (t/3.5) \qquad 7.4$$

for t > 8 yrs.; v_t = average sediment volume after t years and V_{50} = volume after 50 years; the latter is an arbitrary reference.

Regression Equations - H.G. Heinemann's Eqn. (1961) and E.M. Flaxman's Eqn. (1966)

Regression equaticns for the prediction of sediment accumulation have been presented in various papers. For 23 small flood-retarding reservoirs in loess area of Western IOWA, USA, H.G. Heinemann (1961) used the multiple regression method and obtained.

$$y = 22.6+0.886\,Ds - 3.28 \times 10^5 n - 142\times10^{-3}Cs + 0.0308W_s \qquad 7.5$$

where

y = percentage of original reservoir depth filled with sediments.

Ds = total original storage depletion at the end of design period in percent.

n = slope on log-log paper of depth (m) versus capacity (m^3)

Cs = total storage capacity remaining at the end of design period in m^3

Ws = sediment sample volume dry weight in kg/m^3

E.M. Flaxman (1966) analysed 30 locations in nine western states of U.S.A. In a regression analysis for the determination of annual rate of silt deposit, 13 variables were included.

C.W.C.'s Criterion.

The present practice adopted by the Central Water Commission is as follows:

(i) The sediment load and its distribution are worked out for a period of 50 and 100 yrs.

(ii) The minimum drawdown level is fixed slightly above the 'zero' elevation developed after 100 years of accumulation of sediment, with suitable adjustments made for power head and commanded area level, etc.

(iii) The performance of the project is being checked after 50 years through working tables.

By Working out Capacity Inflow Ratio Percent and Finding the Annual Loss of Reservoir Capacity:

For example: The capacity inflow ratio of Bhakra reservoir is 50% which gives annual loss of reservoir capacity as 0.5 per cent (Fig. 7.1) which agrees closely with the figure of 0.57 per cent actually worked out.

By Working Out Trap Efficiency Ratio for Different Reservoir Capacities :

Divide the reservoir capacity into intervals of 10%. Find trap efficiencies for each capacities from the table or graph given above. Multiply the total annual sediment transported by the trap efficiency. Convert this sediment load into volume deposited per year. Divide the volume interval (i.e. 10% of the capacity) by the sediment deposited to get the number of years to fill this volume intervals of 10% capacity. Repeat the procedure and add the number of years for 80%, 70% ...... 20% reservoir capacities.

The trap efficiency of a reservoir decreases with age as the reservoir capacity is reduced by sediment accumulation. This fact will have to be taken into account in any computation for reservoir sedimentation as indicated in Table 7.2 for a reservoir having an average annual inflow of $80x10^6m^3$ and annual sediment inflow of 2,00,000 tonne.

Table 7.2 Evaluation of Life of a Reservoir

Capacity 10^6 m^3	Capacity inflow ratio	Trap Efficiency At indicated volume	Trap Efficiency Average increment percent	Annual Sediment Trapped tonne 2,00,00 col.4	Annual Sediment Trapped m^3 (sp.wt 1.2 t/m^3	Incre-ment volume 10^6 m^3	Year to fill Col.7 ÷ Col.6
40	0.5	96.0					
35	0.4	95.5	95.7	191,400	188,000	8	42.5
24	0.3	95.0	95.2	190,400	187,000	8	42.8
16	0.2	93.0	94.0	188,000	185,000	8	43.2
8	0.1	87.0	90.0	180,000	177,000	8	45.2
					Total		173.7

Say 174 years

The life of certain reservoirs like Hirakud, Krishna, Rampad Sagar etc has been worked out by deltaic theory.

M.A. Gill's Method to Evaluate Life of Reservoir (1988)

Computations using Brune's trap efficiency curves have been simplified by M.A. Gill by developing approximate algebraic equations. These linked the instantaneous reservoir capacity with time in years and other relevant parameters (annual inflow rate of water and sediment transport, the initial capacity of the reservoir, the average specific weight of the sedimements, and so on). The time rate at which reservoir capacity is lost by sedimentation is given by;

$$\frac{dC}{dt} = -\frac{G.E.}{\gamma} \qquad 7.6$$

where, C = reservoir capacity, G = annual rate of inflow of sediment transport, E = trap efficiency, t = time in years, and γ = specific weight of the deposited sediments. E can be expressed algebraically as a function of C/I in which I = annual rate of water inflow.

$$E = fn\ (C/I) \qquad 7.7$$

Algaberaic equations linking E with C/I for each of the three efficiency curves (fine sediment, median and coarse sediment) are as below :

For coarse material

$$E = \div\left(\frac{C^2}{I}\right) \div [0.00003 + 0.0063\left(\frac{C}{I}\right) + 0.9947\left(\frac{C}{I}\right)^2] - \qquad 7.8$$

For median sediment

$$E = \left(\frac{C}{I}\right) \div [0.012 + 1.02\left(\frac{C}{I}\right)] \qquad 7.9$$

For fine material

$$E = \left(\frac{C}{I}\right)^3 - [0.00000102 - 0.00013\left(\frac{C}{I}\right) + 0.0262\left(\frac{C}{I}\right)^2 + 1.0266\left(\frac{C}{I}\right)^3] \qquad 7.10$$

The solution of Eq. 7.6 using Eq. 7.7 can be written as :

$$\phi\left(\frac{C}{I}\right) = \frac{G}{I}\int\frac{dt}{\gamma} \qquad 7.11$$

If the specific weight of the sediments is taken as constant the right side of Eq. 7.11 simplifies to :

$$\phi\left(\frac{C}{I}\right) = \frac{G.t}{\bar{\gamma}\, I} \qquad 7.12$$

in which $\bar{\gamma}$ = average specific weight of the deposited sediments. The functions ϕ (C/I) for the three efficiency curves are given by M.A. Gill as below :

For coarse material

$$\phi\left(\frac{C}{I}\right) = 0.9947\left(\frac{C_o - C}{I}\right) + 0.0063 \ln\left(\frac{C_o}{C}\right) \quad 0.000003\left(\frac{I}{C_o} - \frac{I}{C}\right) \qquad 7.13$$

For median grained material

$$\phi\left(\frac{C}{I}\right) = 0.012\left(\frac{C_o}{C}\right) + 1.02\left(\frac{C_o - C}{I}\right) \qquad 7.14$$

For fine material

$$\phi(\frac{C}{I}) = 1.0266 (\frac{C_o - C}{I}) + 0.0262 \ln (\frac{C_o}{C}) + 0.00013 (\frac{I}{C_o} - \frac{I}{C}) - 0.00000051 (\frac{I^2}{C_o^2} - \frac{I^2}{C^2}) \quad 7.15$$

where

C	=	reservoir capacity
C_o	=	initial capacity of reservoir.

Eq. 7.12 is an approximate solution in as much as γ has been considered constant; actually it varies with time becuase the sediments are consolidated with the passage of time. Also, Eq. 7.12 is somewhat refined, treating γ as a function of time. The refined solution is simple to compute, although the predictions are nearly the same as obtained from Eq. 7.12 in many cases.

Consolidation and Specific Weight

Lane and Koelzer have proposed the empirical relationship for the effect of consolidation on the specific weight of the sediments : (Eqs. 2.5 to 2.14).

These equations can be replaced by the following relation :

$$\gamma = \gamma_1 t^n \quad 7.16$$

where n is a constant; γ = specific weight of deposited sediment and γ_1 = specific weight of sediment after 1 year. Appropriate values of n can be determined using the following relation.

$$\eta = 0.5 \log (1 + \frac{2B}{\gamma_1}) \quad 7.17$$

where B = dimensional constant determined by

$$\gamma = \gamma_1 + B \log t \quad 7.18$$

Using Eq. 7.16 in Eq. 7.11 gives.

$$\phi(\frac{C}{I}) = \frac{G}{I} \int \frac{dt}{\gamma_1 t^n} \quad 7.19$$

which is solved to give :

$$\phi \frac{C}{I} = \frac{G.\ t^{1-n}}{I\ \gamma^{1-n}} \quad \frac{G.\ t}{I\ \gamma^{1-n}} \qquad 7.20$$

Comparison of Eqs. 7.20 and 7.12 reveals that the two are identical if :

$$\bar{\gamma} = \gamma^{1-n} \qquad 7.21$$

A simple calculation shows that the average specific weight using Eq. 7.16 is given by :

$$\bar{\gamma} = \frac{\gamma}{1+n} \qquad 7.22$$

For sufficiently small values of n :

$$\frac{\gamma}{1+n} = \gamma\ (1-n) \qquad 7.23$$

Since n is usually very much smaller than 1 for most of the river sediments, Eq. 7.12 gives reasonably accurate results. M.A. Gill has given the following relation to evaluate $\bar{\gamma}$.

$$\bar{\gamma} = \gamma_1 + \left(\frac{B.t}{t-1}\right)\log\ t - 0.434\ B \qquad 7.24$$

Eq. 7.20 has the advantage that it takes into account the effect of the consolidation of sediments and, at the same time, does not require a trial and error solution.

Example

$C_o = 60 \times 10^6\ m^3$; $I = 95 \times 10^6\ m^3$; $G = 3 \times 10^5\ kg/m^3/km^2$ of drainage area. Drainage area = 300 km^2. Grain size distribution gives 24 per cent sand, 33 percent silt and 43 percent clay. Calculate time by which reservoir will reduce 80% of its capacity.

Solution :

Assuming moderate reservoir drawdown and the trap efficiency curve for the fine sediment.

$$\gamma = \gamma_1 + B\ \log\ (t) = 0.24 \times 1490 + 0.33\ [1185 + 43.3$$

log (t)] + 0.43 [734 + 171.4 log (t)] = 1064.27 + 87.99 log (t).

γ_1 = 1064 and B = 88.

(a) Assume. t = 100 years for which γ_{100} = 1204 kg/m^3 (Eq. 2.14). For fine sediments ϕ (C/I) = 0.5611 using C_o = 60x10^6 m^3; C = 12x10^{6}m^{3}I = 95 x 10^6 m^3/yr. and G = 3 x 10^5 x 3000 = 9 x 10^8 kg/yr.

Substituting values in $\frac{G.t}{\bar{\gamma}.I}$ = 0.5611 gives t = 71.7 years.

correct the values of $\bar{\gamma}$ for t = 71 years: $\bar{\gamma}$ = 1199 kg/m^3. This gives corrected value of t = 71 years.

(b) Using Eqn. 7.17 n = 0.5 log [1 + (2x88)/1064] = 0.0332.

Using Eqn. 7.20 gives t = 71 years, same as in (a).

COMPREHENSIVE METHOD TO EVALUATE LIFE OF RESERVOIR

Principles

With the understanding of the concept of life of reservoir, the following method for working out the life of a reservoir may be adopted (after B.N. Murthy) (1977).

1. First of all, fix up the basic minimum requirement of water which should be sufficient to cater to the needs to the primary use through the cycle of driest years, off-setting the seepage, evaporation and the inaccessible storage. The basic minimum quantity desired in the reservoir may be fixed by operational studies and water management plans based on the past records of inflow data at the dam site. If the reservoir fails to supply this basic minimum, sustaining the above losses, the requirement of a new project would then be considered as necessary and we may term the 'useful' life of the reservoir as ended. The period up to which the reservoir does not encroach upon this basic minimum is termed as the 'useful life' of the project. After fixing the minimum, further steps in computing the life may be taken.

2. Next, ascertain the annual silt load coming into the reservoir, either by suspended sediment data or by actual sedimentation survey of reservoirs.

3. Correction for the inflow of sediment during different periods may be made keeping in view of future upstream developments and other soil conservation measures in the watershed.

4. If the annual silt load has been ascertained by suspended sediment measurements, correct application of density to the silt load is necessary depending upon whether the sediment would be always submerged, etc., and this may be based on the actual experience on the reservoirs where the study on density of deposited sediment has been conducted. At present, studies on some reservoirs have shown the density of the deposits to vary from 480 kg/m^3 to 1600 kg/m^3 in the same reservoir, the average for the entire lake being about 880-1040 kg/m^3 (Reservoir Type-Normally moderate to considerable reservoir drawdown).

5. As only a portion of the incoming silt load will be deposited in the reservoir, find out the trap-efficiency of the reservoir based on either observed data or methods suggested by either Brune or Churchill. Cross check trap efficiency and revised capacity of the lake at interval of 25 years.

6. After ascertaining the silt load which would be deposited, apply correction factor for this consolidation of the deposited sediment. This may be taken at 15 percent of the total load over a period of 200 years. There are other empirical equations suggested by Lane and Koelzer by which the density of deposited sediments after a number of years may be worked out, and hence the volume of silt which it would occupy in a reservoir after a given number of years.

7. After ascertaining the total load for a given period, distribute this load in the reservoir according to the method suggested by Borland and Miller, depending upon the type of the reservoir. Empirical Area-Reduction method is preferable as this method has been developed based on data collection by actual resurvey of reservoirs.

8. After making allowance for trap efficiency for each period of 25 years, also ascertain from the capacity curves whether the physical characteristics of the lake has changed i.e., whether the lake which was under type II has been transformed to type I after sediment deposition over the previous 25 years. If there has been perceptible change, apply the distribution according to the changed type.

9. Work out capacity curves at the intervals of 25,50,75 and 100 years, etc, and check up the quantity of water available in the different allocated zones.

10. For multipurpose reservoir with gated structures where the flood control pool is provided well above the spillway crest level a deposit of 15 percent of the total load during its life period may be assumed in the flood zone. The remaining sediment load will get distributed in the live and dead storage zone.

11. Normally, in any reservoir about 15 percent of the original storage capacity may be taken as inaccessible storage and this is consequent on the limitation of the outlet sill elevations and also due to the formation of silt and sand bars in the reservoir consequent on which water cannot be drawn through and made use of.

12. After obtaining the capacities for different periods say 25,50,75,100 and 200 years, a plot may be developed showing the available capacities against the time period. From this plot it is easy to ascertain the period when the projects fail to meet the minimum basic demand as originally fixed, and this period is termed as the 'useful life' of the project.

13. With the available storage as worked out for different periods, the benefit-cost ratio may be worked out and when this ratio falls below unity, the period in time may be termed as 'Economic Life' of the reservoir.

14. In case of multipurpose reservoirs the reservoir may fail to meet the demands of requirement of water for irrigation, power, and water supply, but still, the life cannot be termed as over as the reservoir would be useful for flood control purposes. Thus, the term, 'life' of reservoir has different meaning for different types of reservoirs.

The case of Nizamsagar in Andhra Pradesh in which the dead storage capacity has been lost fully due to sedimentation with an encroachment of 45 percent in live storage over the past 37 years, has been taken as an example and a plot showing the available capacity in different allocated zones against time, and also the distribution pattern of sediment and capacity of reservoir during different periods has been developed and is shown in Figures 7.1 & 7.2. In this case, the sediment for various periods have been distributed by trigonometric method. From this type of plot it would be easy to ascertain the period when the useful life of the reservoir would be ended or the period when the project would become economically inefficient, by ascertaining the requirement of basic minimum quantity of storage catering to the needs of primary use, and the benefit-cost ratio when it would fall below unity.

Design Example Bhakra Reservoir (Detailed Working Out of the Life of Reservoir - C.B.I. & P Technical Report No. 19. Sept. 1980 by B.N. Murthy).

(1) The Bhakra Reservoir has the following features:

(i) Catchment area = 56720.78 sq km (21,900 sq. miles net).

(ii) Mean annual run-off = 1.599 million ha m (13 million acre-ft).

(iii) Length of reservoir 627.64 km (390 miles), average width 90.12 km (56 miles).

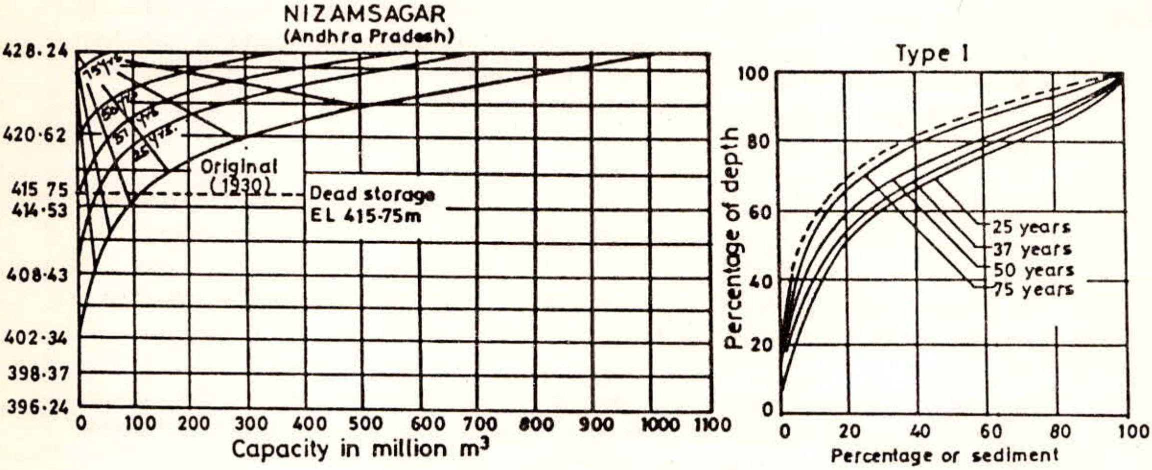


Fig 7.1 The Above is reduced capacity curves for different ages drawn by trigonometric method, assuming 12.70 million m^3 of load annually.

Flood pool.....El. 426.87 m to 428.24
Live storage...El.426.87 m to 415.75 m
Dead storage...El.415.75 m and below
Average bed...El.398.37 m
Catchment area...21694 sq.km
Net sediment... 18524 sq.km contributing area

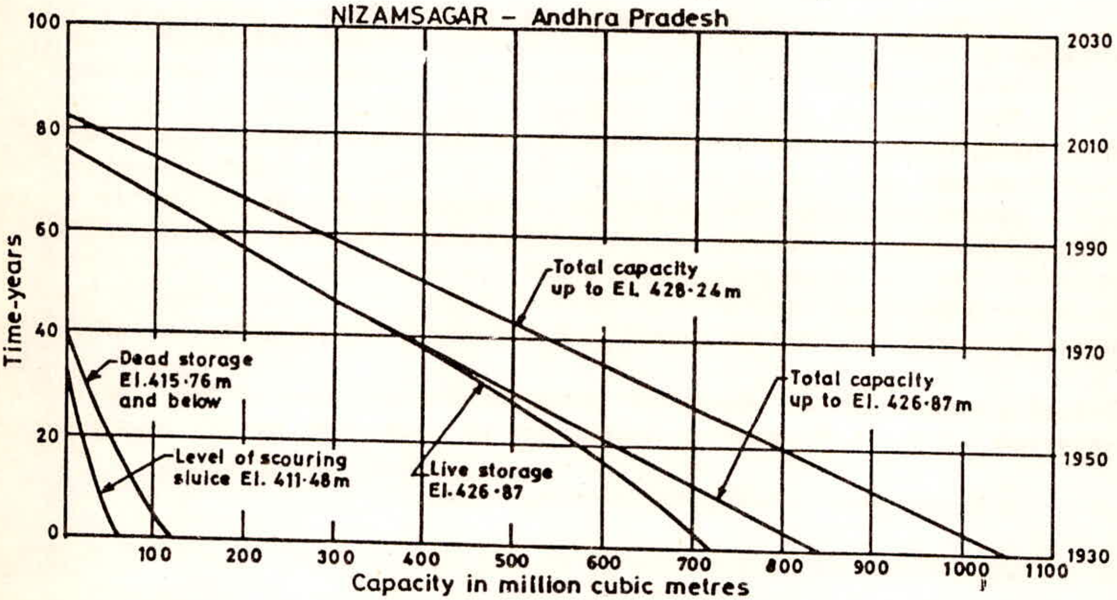


Figure 7.2 The above is based on an annual average sediment accumulation of 12.70 million m^3 derived from the observed sediment load of 471.2 million m^3 in 37 years 11930 to 19671. Correction for compaction etc. not taken into consideration.

(iv) Submergence area at EL. 1690 = 16867.311 ha (4168 acres).

Dead Storage El. 1462, Capacity = 0.24 million ha m (0.97 million acre ft).

Normal Pool El. 1680, Capacity = 0.91 million ha m (7.4 million acre-fit).

Full reservoir level El. 1690, Capacity = 0.98 million ha m (8 million acre ft).

(2) C/I ratio = $\frac{7.4}{13}$ = 0.6. According to Brune's curve the trap efficiency of the reservoir is 97 percent.

(3) From reservoir depth capacity relationship, it is found that the reservoir falls into two types, viz., Type II and Type III, the reciprocal of the slope (M'value) being 2.70 for some portion and 2.36 for the remaining. From operation consideration particle size of sediment, etc., the reservoir has been classified as Type II for distribution of sediment.

(4) It is found that the life of the reservoir would cease to be economical when the loss of reservoir capacity would be 75 percent of the total capacity, i.e., when the basic minimum capacity falls below 0.22 million ha m (1.8 million acre ft).

(5) The annual suspended sediment load at the site is 34.54 million tonnes (34 million tonnes). With 15 percent bed load, the total load come to say, 40 million tonnes (39 million tonnes).

Assuming a density of 1041.3 kg/m^3 (65 lb/cu ft) the annual volume of silt load would be :

$$\text{Silt Volume} = \frac{40 \times 10^6 \times 2240}{65 \times 43560}$$

$$= 32{,}000 \text{ acre ft } (3936.0 \text{ ha m}).$$

Actual reservoir surveys have also shown this volume of annual silt load, and hence the density assumed may taken as correct.

(6) Assuming 15% consolidation over 200 years, and making allowance for trap efficiency, etc., the annual silt load has been considered at 3690 ha m (30,000 acre ft) per year.

(7) No correction for the silt has been made for future 'upstream engineering' in

the watershed or the effects of any type of watershed management practices, etc. Even so, its effect would be marginal.

(8) Empirical Area-Reduction method has been considered for distribution of sediment load during the different periods of life.

(9) If is seen that for a period of 100 years, the capacity inflow ratio still remains high and consequently trap efficiency of the reservoir is also found to be in the order ranging from 95-97%. Hence in the incoming sediment load for distribution, up to 100 years no change has been effected, in the value of trap efficiency.

For the next 100 years the annual sediment rate has been assumed at 30,000x0.90 = 27,000 acre ft (3321 ha m) as the trap efficiency ranges between 95 to 85% during this period, i.e. 27,000 acre ft (3321 ha m) of silt load annually has been assumed for the next 100 years distribution.

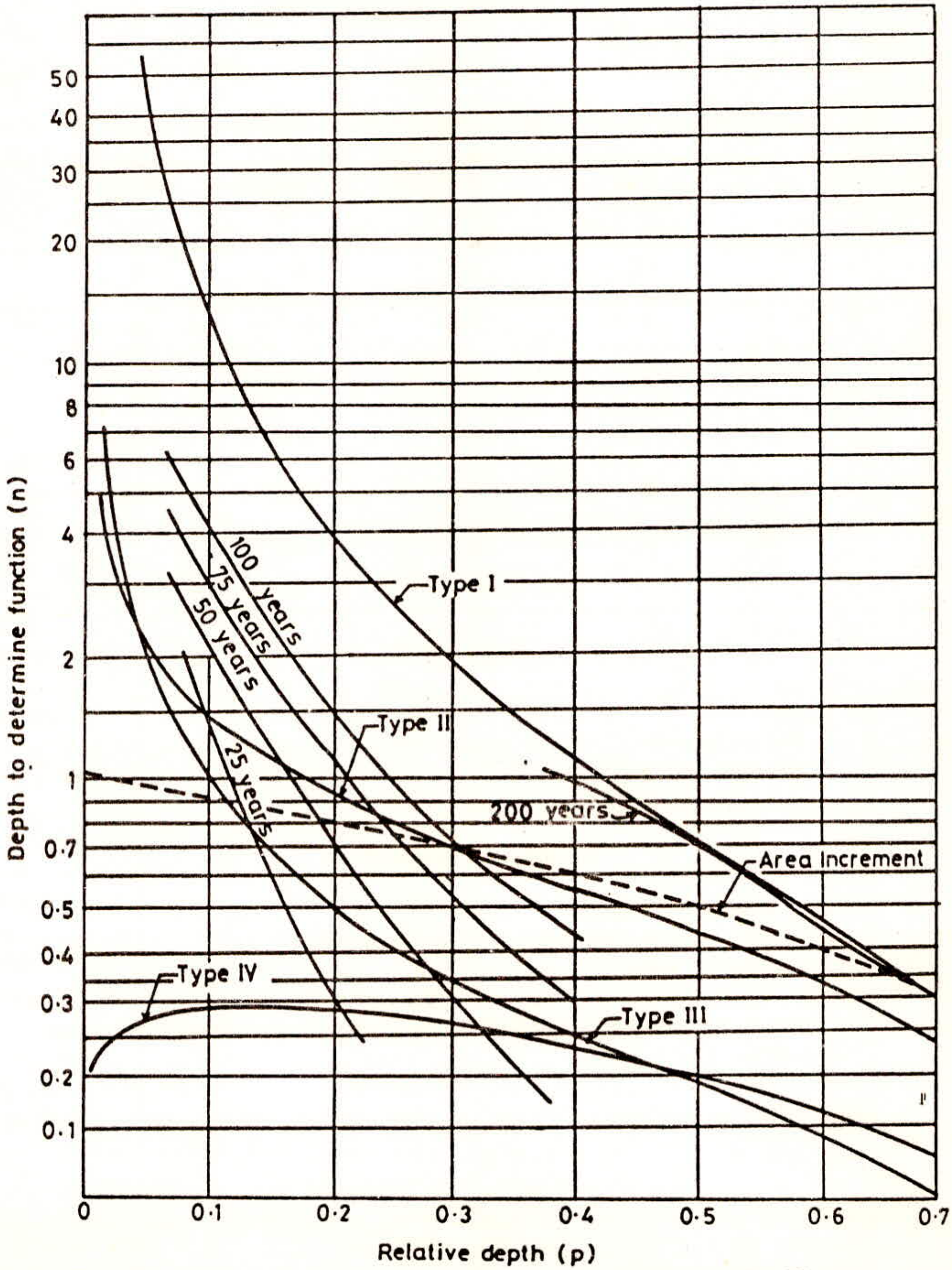
(10) For the first 50 years, the reciprocal values of the slope of the capacity curve does not show any abrupt change, and the 'M' value varies from 2.36 to 3.3 and hence the distribution has been made on the basis of reservoir Type II.

For the remaining period 75-200 years, 'M' value ranges from 4 and above and the distribution has been made on Type I basis as the sediment would mostly be distributed in the upper regions with the building up of reservoir delta. It is seen that h'_p curve computed for Type I reservoir does not intersect the h_p curve for the type of the reservoir determined. For the periods 75,100, and 200 years the depth of sediment at dam (zero elevation) has been worked out by the area increment-method. All these h'_p curves intersect on the h_p values plotted for the area increment method.

(11) Empirical area-reduction method has been adopted and the relative depth (P) for 25,50,75,100 and 200 years at the dam are shown in Figure 7.3 and Tables 7.3 to 7.7 to show the computed elevation of deposited sediment at the dam for each of these periods. The sediment disposition computations and the revised capacity for different periods 25,50,75,100 and 200 years are shown in the Tables 7.8 to 7.12.

(12) After obtaining the new capacities of the reservoir for different periods, a plot has been developed (Figure 7.4) showing the available capacity in the different allocated zones and also the total capacity against the time period.

(13) From this plot we can read when the basic minimum requirement of water as assumed in the beginning, i.e., 0.22 million ha m (1.8 million acre ft) is going to be encroached upon. From the plot this would be after 180 years say.



Reproduction of figure 7.3 of C.B.I. & P. Technical Report No 19, September 1980 Page 79

TABLE 7.3 Direct Determination of Elevation of Sediment Deposited at the Dam.

(Empirical area-reduction method)

Age : 25 years
Reservoir : Bhakra Project : India

S = 7,50,000 acre-ft (92250 ha-m) H = 1680-1150 = 530 ft(161.54 m)

Elevation metre(ft)	(p)	V(pH) x10[3]	S-V(pH) x10[3]	HA(pH) x10[3]	h'(p)
(1)	(2)	(3)	(4)	(5)	(6)
350.52 (1150)	0	0	750	0	infinite
365.76 (1200)	0.093	20	730	477	1.53
381.0 (1250)	0.189	110	640	1700	0.376
396.24 (1300)	0.283	350	400	3180	0.126
411.48 (1350)	0.376	710	40	4620	-

(Type : II)

p_o = 0.093
p_oH = 50
Bottom elevation = 1150
Elevation of sediment deposited at dam = 1200

Notation of Symbols

p = rélative depth of reservoir,
V(pH) = reservoir capacity in acre-ft at a given elevation,
S = total sediment inflow in acre-ft,
A(pH) = reservoir area in acres at a given elevation, and
h' (p) = a function of the reservoir and its anticipated sediment storage expressed as follows:

$$h'(p) = \frac{S - V(pH)}{HA(pH)}$$

Reproduction of Table No. 7.1 of C.B.I. & P Technical Report No. 19 September, 1980 Page 80.

TABLE 7.4 Direct Determination of Elevation of Sediment Deposited at the Dam.
(Empirical area-reduction method)

Age : 50 years
Reservoir : Bhakra Project : India

S = 1500,000 acre-ft (184500 ha-m) H = 1680-1150 = 530 ft(161.54 m)

Elevation metre(ft)	(p)	V(pH) $x10^3$	S-V(pH) $x10^3$	HA(pH) $x10^3$	h'(p)
(1)	(2)	(3)	(4)	(5)	(6)
350.52 (1150)	0	0	1500	0	infinite
365.76 (1200)	0.093	20	1480	477	3.11
381.0 (1250)	0.189	110	1390	1700	0.82
396.24 (1300)	0.283	350	1150	3180	0.362
411.48 (1350)	0.376	710	790	4620	0.171
426.72 (1400)	0.472	1210	290	5820	0.050

(Type : II)

p_o = 0.160
p_oH = 8550
Bottom elevation = 1150
Elevation of sediment deposited at dam = 1235

Notation of Symbols

p = relative depth of reservoir,
V(pH) = reservoir capacity in acre-ft at a given elevation,
S = total sediment inflow in acre-ft,
A(pH) = reservoir area in acres at a given elevation, and
h'(p) = a function of the reservoir and its anticipated sediment storage expressed as follows:

$$h'(p) = \frac{S - V(pH)}{HA(pH)}$$

Reproduction of Table No. 7.2 of C.B.I. & P Technical Report No. 19 September, 1980 Page **81**.

TABLE 7.5 Direct Determination of Elevation of Sediment Deposited at the Dam.

(Empirical area-reduction method)

Age : 75 years

Reservoir : Bhakra Project : India

S = 2250,000 acre-ft (276750 ha-m) H = 1680-1150 = 530 ft(161.54 m)

Elevation metre(ft)	(p)	V(pH) x10³	S-V(pH) x10³	HA(pH) x10³	h'(p)
(1)	(2)	(3)	(4)	(5)	(6)
350.52 (1150)	0	0	2250	0	infinite
365.76 (1200)	0.093	20	2230	477	4.58
381.0 (1250)	0.189	110	2140	1700	1.26
396.24 (1300)	0.283	350	1900	3180	0.598
411.48 (1350)	0.376	710	1540	4620	0.334
426.72 (1400)	0.472	1210	1040	5820	0.179
441.96 (1450)	0.566	1810	440	7100	0.062

(Type : I)

p_o = 0.255

p_oH = 135 ft(41.15 m)

Bottom elevation = 1150

Elevation of sediment deposited at dam = 1285

Notation of Symbols

p = relative depth of reservoir,

V(pH) = reservoir capacity in acre-ft at a given elevation,

S = total sediment inflow in acre-ft,

A(pH) = reservoir area in acres at a given elevation, and

h'(p) = a function of the reservoir and its anticipated sediment storage expressed as follows:

$$h'(p) = \frac{S - V(pH)}{HA(pH)}$$

Reproduction of Table No. 7.3 of C.B.I. & P Technical Report No. 19 September, 1980 Page 82.

TABLE 7.6 Direct Determination of Elevation of Sediment Deposited at the Dam.
(Empirical area-reduction method)

Age : 100 years
Reservoir : Bhakra Project : India

S = 3000,000 acre-ft (369000 ha-m) H = 1680-1150 = 530 ft(161.54 m)

Elevation metre(ft)	(p)	V(pH) x10³	S-V(pH) x10³	HA(pH) x10³	h'(p)
(1)	(2)	(3)	(4)	(5)	(6)
350.52 (1150)	0	0	3000	0	infinate
365.76 (1200)	0.093	20	2980	477	6.20
381.00 (1250)	0.189	110	2890	1700	1.70
396.24 (1300)	0.283	350	2650	3180	0.833
411.48 (1350)	0.376	710	2290	4620	0.498
426.72 (1400)	0.472	1210	1290	5820	0.308
441.96 (1450)	0.566	1810	1140	7100	0.168
457.20 (1500)	0.662	2580	420	8850	0.470

(Type : I)

p_o = 0.31
p_oH = 167
Bottom elevation = 1150
Elevation of sediment deposited at dam = 1150+167
= 3317 ft(401.42 m)

Notation of Symbols

p = relative depth of reservoir,
V(pH) = reservoir capacity in acre-ft at a given elevation,
S = total sediment inflow in acre-ft,
A(pH) = reservoir area in acres at a given elevation, and
h'(p) = a function of the reservoir and its anticipated sediment storage expressed as follows:

$$h'(p) = \frac{S - V(pH)}{HA(pH)}$$

Reproduction of Table No. 7.4 of C.B.I. & P Technical Report No. 19 September. 1980 Page 83.

TABLE 7.7 Direct Determination of Elevation of Sediment Deposited at the Dam.

(Empirical area-reduction method)

Age : 202 years

Reservoir : Bhakra   Project : India

S = 5700,000 acre-ft (701100 ha-m)   H = 1680-1150 = 530 ft(161.54 m)

Elevation metre(ft)	(p)	V(pH) x10³	S-V(pH) x10³	HA(pH) x10³	h'(p)
(1)	(2)	(3)	(4)	(5)	(6)
411.48 (1350)	0.376	710	4990	4620	1.080
426.72 (4200)	0.472	1210	4490	5820	0.771
441.96 (1450)	0.566	1810	3890	7100	0.548
457.20 (1500)	0.662	2580	3140	8850	0.352
472.44 (1550)	0.755	3500	2200	11289	0.194

(Type : I)

p_o	=	0.670
p_oH	=	357
Bottom elevation	=	1150
Elevation of sediment deposited at dam	=	1507

Notation of Symbols

p = relative depth of reservoir,

V(pH) = reservoir capacity in acre-ft at a given elevation,

S = total sediment inflow in acre-ft,

A(pH) = reservoir area in acres at a given elevation, and

h'(p) = a function of the reservoir and its anticipated sediment storage expressed as follows:

$$h'(p) = \frac{S - V(pH)}{HA(pH)}$$

Reproduction of Table No. 7.5 of C.B.I. & P Technical Report No. 19 September, 1980 Page 80.

Table 7.8 Sediment Disposition Computations.

(Empirical area-reduction method)

Age : 25 years

Reservoir : Bhakra Project : India

Total sediment inflow : 92250.0 ha-m (750,000 acre-ft)

Eleva-tion metre (ft)	Original area ha (acres)	Original capacity ha-m (acre-ft)	Relative Depth	Ap Type I	Sediment area (ha) (acre)	Sediment volume ha-m (acre-ft)	Accumulated sediment volume ha-m (acre-ft)	Revised area ha (acres)	Revised capacity ha-m (acre-ft)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
512.06 (1680)	15378.07 (38,000)	910200.0 (7400,000)	1.000	0	0	1926.18 (15,660)	92250.0 (750,000)	15378.07 (38,000)	817950.0 (6650.000)
502.92 (1650)	13759.32 (34,000)	772440.0 (6280,000)	0.945	0.720	422.89 (1045)	7816.65 (63,550)	90323.82 (734,340)	13336.83 (32,956)	682116.18 (5545,660)
487.68 (1600)	11047.92 (27,300)	587940.00 (4780,000)	0.850	1.030	605.41 (1496)	9889.2 (80,400)	82513.32 (670,840)	10442.51 (25,804)	505426.68 (4109,160)
472.44 (1550)	8619.81 (21,300)	436650.0 (3550,000)	0.755	1.185	696.46 (1721)	10891.65 (88,550)	72624.12 (590,440)	7923.34 (19,579)	364025.83 (2959,60)
457.20 (1500)	6798.72 (16,800)	317340.0 (2580,000)	0.662	1.255	737.33 (1822)	11291.4 (91,800)	61732.47 (501,890)	6061.38 (14,973)	255607.53 (2078,110)
441.96 (1450)	5382.32 (13,300)	222630.0 (1810,000)	0.566	1.275	749.07 (1851)	11248.35 (91,450)	50441.07 (410.090)	4633.25 (11,449)	172188.93 (1399,910)
426.72 (1400)	4451.54 (11,000)	148830.0 (1210,000)	0.475	1.245	731.67 (1808)	10762.50 (87.500)	39192.72 (318,640)	3719.37 (9,192)	109637.25 (891,360)
411.48 (1350)	3561.23 (8,800)	87330.0 (710,000)	0.376	1.165	684.73 (1692)	7065.12 (57,440)	28430.22 (231,140)	2876.51 (7,105)	58899.78 (478,860)
400.81 (1315)	2751.86 (6,800)	55350.0 (450,000)	0.312	1.095	643.45 (1590)	2896.65 (23,550)	21365.1 (173,700)	2108.41 (5,210)	33984.9 (276,300)
396.24 (1300)	2428.11 (6,000)	43050.0 (350,000)	0.283	1.068	627.66 (1551)	9003.60 (73,200)	18468.45 (150,150)	1800.45 (4,443)	24581.55 (199,850)
381.0 (1250)	1294.99 (3,200)	13530.0 (110,000)	0.189	0.950	558.06 (1379)	7004.85 (56,950)	9464.85 (76,950)	736.83 (1.820)	4065.15 (33,050)
365.76 (1200)	364.21 (900)	2460.0 (20,000)	0.093	0.650	354.21 (900)		2460.0 (20,000)	0	
350.52 (1150)	0	0	-	-	-			-	

Supplement

365.76 (1200)	364.21 (900)	0.093	0.680	$K = \frac{900}{0.680} = 1324$ (Used K = 1452)

Reproduction of Table No. 7.6 of C.B.I. & P Technical Report No. 19 September, 1980 Page 85.

Table 7.9 Sediment Disposition Computations.

(Empirical area-reduction method)

Age : 50 years

Reservoir : Bhakra Project : India

Total sediment inflow : 184500.0 ha-m (1500,000 acre-ft)

Elevation metre (ft)	Original area ha (acres)	Original capacity ha-m (acre-ft)	Relative Depth	Ap Type II	Sediment area ha (acre)	Sediment volume ha-m (acre-ft)	Accumulated sediment volume ha-m (acre-ft)	Revised area ha (acres)	Revised capacity ha-m (acre-ft)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
512.06	15378.07	910200.0				3959.37	184500.00	15378.07	725700.0
(1680)	(38,000)	(7400,000)	1.000	0	0	(32,190)	(1500.000)	(38,000)	(5900,000)
502.95	13759.32	772440.0			868.45	16039.20	180540.63	14509.61	591899.37
(1650)	(34,000)	(6280,000)	0.945	0.720	(2146)	(130,400)	(1467.810)	(35,854)	(4812,190)
487.68	11047.92	587940.00			1242.38	20301.45	164501.43	9805.54	423438.37
(1600)	(27,300)	(4780,000)	0.850	1.030	(3070)	(165,050)	(1337.410)	(24,230)	(3442,590)
472.44	8619.81	436650.0			1429.35	22364.47	144200.28	7190.46	292449.72
(1550)	(21,300)	(3550,000)	0.755	1.185	(3532)	(81.825)	(1172.360)	(17,768)	(2377,640)
457.20	6798.72	317340.0			1513.93	23188.57	121835.80	5284.79	195504.19
(1500)	(16,800)	(2580,000)	0.662	1.255	(3741)	(188,525)	(990,535)	(13,059)	(1589,465)
441.96	5382.32	222630.0			1537.80	23096.32	98647.23	3844.51	123982.77
(1450)	(13,300)	(1810,000)	0.566	1.275	(3800)	(187,775)	(802,010)	(9,500)	(1007,990)
426.72	4451.54	148830.0			1501.79	22087.72	75550.90	2949.75	73279.09
(1400)	(11,000)	(1210,000)	0.472	1.245	(3711)	(179,575)	(614.235)	(7,289)	(595,765)
411.48	3561.23	87330.0			1405.07	14499.24	53463.18	2156.16	33866.82
(1350)	(8,800)	(710,000)	0.376	1.165	(3472)	(117,880)	(434,660)	(5,328)	(275,340)
400.81	2751.86	55350.0			1320.89	5947.29	38963.94	1430.97	16386.06
(1315)	(6,800)	(450,000)	0.312	1.095	(3264)	(48,352)	(316.780)	(3,536)	(133,220)
396.24	2428.11	43050.0			1288.11	18493.05	33016.64	1140.00	10033.35
(1300)	(6,000)	(350,000)	0.283	1.068	(3183)	(150,350)	(268.428)	(2,817)	(81,572)
381.0	1294.99	13530.0			1145.66	4683.49	14523.59	149.33	-
(1250)	(3,200)	(110,000)	0.189	0.950	(2831)	(38,078)	(118,078)	(369)	
376.43	908.92	9840.00			908.42		9840.0	0	-
(1235)	(2,246)	(80,000)	0.160	0.890	(2246)		(80,000)		

Supplement

376.43 908.92

(1235) (2246) 0.160 0.890

$$K = \frac{2246}{0.890} = 2524$$

(Used K = 2980)

Reproduction of Table No. 7.7 of C.B.I. & P Technical Report No. 19 September, 1980 Page 86.

Table 7.10 Sediment Disposition Computations.

(Empirical area-reduction method)

Age : 75 years

Reservoir : Bhakra Project : India

Total sediment inflow : 276750.0 ha-m (2250,000 acre-ft)

Elevation metre (ft)	Original area ha (acres)	Original capacity ha-m (acre-ft)	Relative depth	Ap Type I	Sediment area ha (acre)	Sediment volume ha-m (acre-ft)	Accumulated sediment volume ha-m (acre-ft)	Revised area ha (acres)	Revised capacity ha-m (acre-ft)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
512.06	15378.07	910200.0				11446.38	276753.32	15378.0	633446.6
(1680)	(38,000)	(7400,000)	1.000	0	0	(93,060)	(2250,027)	(38,000)	(5149,973)
502.95	13759.32	772440.0			2510.67	41887.65	265306.94	11248.65	507133.05
(1650)	(34,000)	(6280,000)	0.945	1.57	(6204)	(340,550)	(2156,967)	(27,796)	(4123,033)
487.68	11047.92	587940.0			3006.81	44842.72	223382.39	8041.11	364557.60
(1600)	(27,300)	(4780,000)	0.850	1.88	(7430)	(364.575)	(1816,117)	(19,870)	(2963,883)
472.44	8619.81	436650.0			2894.72	41318.77	178539.66	5725.09	251960.33
(1550)	(21,300)	(3550,000)	0.755	1.81	(7153)	(335.925)	(1451,542)	(14.147)	(2048,458)
457.20	6798.72	317340.0			2543.04	35242.57	137220.89	4255.6	180119.10
(1500)	(16,800)	(2580,000)	0.662	1.59	(6284)	(286.525)	(1115.617)	(10,516)	(1464,383)
441.96	5382.32	222630.0			2095.06	27948.67	101978.31	3287.26	120651.68
(1450)	(13,300)	(1810,000)	0.566	1.31	(5177)	(227,225)	(829,092)	(8,123)	(980,908)
426.72	4451.54	148830.0			1583.13	20414.92	74029.64	2868.41	74800.36
(1400)	(11,000)	(1210,000)	0.472	0.99	(3912)	(165,975)	(601,867)	(7,088)	(608,133)
411.48	3561.23	87330.0			1103.58	13609.95	53614,71	2457.66	33715.28
(1350)	(8,800)	(710,000)	0.376	0.69	(2727)	(110,650)	(435,892)	(6,073)	(274,108)
396.24	2428.11	43050.0			687.56	6180.13	40004.76	1740.55	3044.86
(1300)	(6,000)	(350,000)	0.283	0.43	(1699)	(50,245)	(325,242)	(4,301)	(24,755)
391.67	2023.43	33825.0			2023.43		33825.0	-	0
(1285)	(5,000)	(275,000)	0.255	0.36	(5000)		(275,000)		
381.0	1294.99	13530.0							
(1250)	(3,200)	(110.000)	0.189	0.21	-				
365.76	364.21	2460.0							
(1200)	(900)	(20,000)	0.093	0.06	-				
350.52	0	0	0	0					
(1150)									

Supplement

391.67	2023.43	33825.0			
(1285)	(5000)	(275,000)	0.255	0.36	$K = \frac{5000}{0.36} = 13,889$ (Used K = 3952)

Reproduction of Table No. 7.8 of C.B.I. & P Technical Report No. 19 September, 1980 Page 87.

Table 7.11 Sediment Disposition Computations.

(Empirical area-reduction method)

Age : 100 years

Reservoir : Bhakra Project : India

Total sediment inflow : 369000.0 ha-m (3,000,000 acre-ft)

Elevation metre (ft)	Original area ha (acres)	Original capacity ha-m (acre-ft)	Relative depth	Ap Type I	Sediment area ha (acres)	Sediment volume ha-m (acre-ft)	Accumulated sediment volume ha-m (acre-ft)	Revised area ha (acres)	Revised capacity ha-m (acre-ft)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
512.06 (1680)	15378.07 (38,000)	910200.0 (7400,000)	1.00	0	0	14824.57 (120,525)	369050.55 (3000,411)	15378.0 (38,000)	541200.0 (4400,000)
502.92 (1650)	13759.32 (34,000)	772440.0 (6280,000)	0.945	1.57	3251.65 (8035)	54295.27 (441,425)	354225.97 (2879,886)	10507.67 (25,965)	418214.02 (3400,114)
487.68 (1600)	11047.92 (27,300)	587940.00 (4780,000)	0.850	1.88	3893.89 (9622)	58074.45 (472,150)	299930.70 (2438,461)	7154.04 (17,678)	288009.29 (2341,539)
472.44 (1550)	8619.81 (21,300)	430500.0 (3500,000)	0.755	1.81	3749.01 (9264)	53511.45 (435,050)	241856.25 (1966,311)	4870.80 (12,036)	188643.74 (1533,689)
457.20 (1500)	6798.72 (16,800)	317340.0 (2580,000)	0.662	1.59	3293.33 (8138)	45642.22 (371,075)	188345.10 (1531,261)	3505.39 (8,622)	128994.89 (1048,739)
441.96 (1450)	5382.32 (13,300)	222630.0 (1810,000)	0.566	1.31	2713.42 (6705)	36198.90 (294,300)	142702.87 (1160,186)	2668.90 (6,595)	79927.12 (649,814)
426.72 (1400)	4451.54 (11,000)	148830.0 (1210,000)	0.472	0.99	2050.54 (5067)	26438.85 (214,950)	106503.97 (865,886)	2401.00 (5,933)	42326.02 (344,114)
411.48 (1350)	3561.23 (8,800)	87330.0 (710,000)	0.376	0.69	1428.94 (3531)	21271.13 (172,936)	80065.13 (650,936)	2132.29 (5,269)	7264,87 (59,064)
401.42 (1317)	2812.11 (6,950)	58794.0 (478,000)	0.315	0.51	2812.56 (6950)		58794.0 (478,000)	0	0
396.24 (1300)	2428.11 (6,000)	43050.0 (350,000)	0.283	0.43					
381.0 (1250)	1294.99 (3,200)	13530.0 (110.000)	0.189	0.21					
365.76 (1200)	364.21 (900)	2460.0 (20,000)	0.093	0.06					
350.52 (1150)	0	0	0	0					

Supplement

401.42 (12317)	2812.56 (6,950)	58794.00 (478,000)	0.315	0.51

$$K = \frac{6950}{0.51} = 13627$$

(Used K = 5118)

Reproduction of Table No. 7.9 of C.B.I. & P Technical Report No. 19 September, 1980 Page 88.

Table 7.12 Sediment Disposition Computations.

(Empirical area-reduction method)

Age : 200 years

Reservoir : Bhakra Project : India

Total sediment inflow : 701100.0 ha-m (57,00,000 acre-ft)

Elevation metre (ft)	Original area ha (acres)	Original capacity ha-m (acre-ft)	Relative depth	Ap Type I	Sediment area ha (acre)	Sediment volume ha-m (acre-ft)	Accumulated sediment volume ha-m (acre-ft)	Revised area ha (acres)	Revised capacity ha-m (acre-ft)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
512.06	15378.07	910200.0					701095.44		209104.55
(1680)	(38,000)	(7400,000)	1.00	0	0		(5699,963)		(1700,037)
502.92	13759.32	772440.0			6950.07	31686.03	669409.41		103030.58
(1650)	(34,000)	(6280,000)	0.945	1.57	(17,174)	(257,610)	(5442,353)		(837,647)
487.68	11047.92	587940.00			8322.36	116047.42	553361.99		34578.00
(1600)	(27,300)	(4780,000)	0.850	1.88	(20,565)	(943,475)	(4498,878)		(281,122)
472.44	8619.81	430500.0			8012.38	124119.30	429242.69		1257.31
(1550)	(21,300)	(3500,000)	0.755	1.81	(19,799)	(1009,100)	(3489,778)		(10,222)
459.33	7041.53	330870.0			7041.53	98372.69	330870.0		0
(1507)	(17,400)	(2690,000)	0.674	1.63	(17,400)	(799,778)	(2690,000)		
457.20	6798.72	317340.00							
(1500)	(16,800)	(2580,000)	0.662						
441.96	5382.32	222630.0							
(1450)	(13,300)	(1810,000)	0.566						
426.72	4451.54	148830.0							
(1400)	(11,000)	(1210,000)	0.472						
411.48	3561.23	87330.0							
(1350)	(8,800)	(710,000)	0.376						
396.24	2428.11	43050.0							
(1300)	(6,000)	(350,000)	0.283						
381.0	1294.99	13530.0							
(1250)	(3,200)	(110,000)	0.189						
365.76	364.21	2460.0							
(1200)	(900)	(20,000)	0.093						
350.52	0	0	0						
(1150)									
					Supplement				
459.33	7041.53	330870.0							
(1507)	(17,400)	(2690,000)	0.674	1.63		K = 10675			

(Used K = 10939)

Reproduction of Table No. 7.10 of C.B.I. & P Technical Report No. 19 September, 1980 Page

Therefore, the useful life of Bhakra Reservoir would be for 180 years, and this we may term as 'Life of Bhakra Reservoir'.

Statement 2 (5 sheets) gives data in respect of Indian reservoirs and also the methods followed in calculating life of reservoirs.

PRACTICES FOLLOWED TO ESTIMATE LIFE OF RESERVOIRS

Tennesse Valley Authority (TVA) Practice.

When the project is envisaged, the silt load is normally assessed by suspended-load observations on the stream and the life of the reservoir is estimated by assuming a certain density of the deposit. After impounding of the reservoir, capacity surveys by electronic equipment or by other methods actually indicate the silt load trapped in the reservoir and from this the future expected sediment load and the life of the reservoir may be correctly estimated.

The TVA practice to estimate the life of reservoir is to use the 'Step Method' based in Brune's trap-efficiency curve as related to the capacity-inflow ratio (Fig. 3.3). Initially the computations are made for steps of 10-,20 and 30-year intervals as the trap efficiency changes with time because of a reduction in the capacity of reservoir due to silt deposition. If trap efficiencies change more rapidly, as is the case at the end of the period when the reservoir approaches the point of being filled with sediment, shorter time intervals are considered in the computations (example given herein).

Example (after C.B.I. & P Technical Report No. 19 Sept. 1980)

Estimate the time required to fill a reservoir with sediment using Brune's trap-efficiency relationship with the following data:

Capacity of reservoir	=	1,85,961.24 ha m
Annual sediment load	=	194.58 ha m
Annual average inflow to the reservoir	=	5,77,032.48 ha m

Solution

The computation are given in Table 7.13, the columns of which are explained below:

(1) = Time interval in steps of 10 years or so depending upon the change of the trap efficiency due to sediment deposition.

(2) = Capacity of reservoir at the beginning of time period and is equal to original capacity less the silt deposit.

Therefore this is equal to (2)-(6) lagged by one time unit.

(3) = Average annual inflow.

(4) = Capacity inflow ratio (2)/(3)

(5) = Trap efficiency read from Fig. 3.3 corresponding to capacity inflow ratio of (4).

(6) = Sediment deposited in the reservoir during the period of (1) = (annual sediment rate 194.50)x(number of years)x(trap efficiency during the period).

Table 7.13 Estimate of Life of Reservoir-Brune's Trap-Efficiency Relationship

Time (year) inflow (ha-m)	Capacity (ha-m) ratio (2)/(3)	Average annual inflow (ha m)	Capacity inflow (ham)	Trap efficiency (Fig. 3.3 %)	Sediment deposited (ha-m)
0	1,85,961.24	5,77,032.48	0.322	95	
10	1,84,112.55	5,77,032.48	0.319	95	1848.69*
20	1,82,263.86	5,77,032.48	0.316	95	1848.69
50	1,76,717.79	5,77,032.48	0.306	95	5546.07
.100	1,67,474.95	5,77,032.48.	0.290	95	9242.83
200	1,48,989.28	5,77,032.48	0.258	94	18485.67
300	1,30,697.95	5,77,032.48	0.227	94	18291.33
400	1,12,406.62	5,77,032.48	0.195	93	18291.33
500	94,309.63	5,77,032.48	0.163	91	18096.90
600	76,602.55	5,77,032.48	0.133	90	17707.08
700	59,089.81	5,77,032.48	0.102	87	17512.74
800	42,161.32	5,77,032.48	0.073	83	16928.49
900	26,011.42	5,77,032.48	0.045	76	16149.90
1000	23,523.13	5,77,032.48	0.022	62	14788.29
1030	7605.70	5,77,032.48	0.013	50	3618.66
1060	4685.68	5,77,032.48	0.0081	39	2918.79
1080	3167.86	5,77,032.48	0.0054	29	1517.82
1100	2038.72	5,77,032.48	0.0035	18	1129.14
1120	1337.62	5,77,032.48	0.0023	6	701.10
1140	1103.92	5,77,032.48	0.0019	2	233.70
1150	1064.50	5,77,032.48	0.0018	0	39.36

* 1848.69 = 194.58x10x0.95

Impact of Siltation on the Useful Life of Large Reservoirs

Practice in Japan

Owing to the steep gradient of the river bed and precipitous configuration of the catchment area, most of the rivers in Japan carry heavy sand and gravel which accumulate in great bulk in reservoirs.

The general practice is to allow for the amount of silt which is carried in 100 years. In most of the multipurpose projects the silt load is estimated between 1.9 to 3.81 ha m/100 sq km/yr. but there are some schemes where this value is taken as 2.46 ha m/100 sq km/year. The sedimentation data collected from 106 reservoirs in Japan, 39 in USA and 1 in Taiwan have been analysed and the following relationships have been developed.

$$r_s = 0.214(C/I)^{-0.473} \qquad 7.25$$

and

$$t_s = 467(C/I)^{0.473} \qquad 7.26$$

where

r_s = annual mean silt deposition rate (%)

C = original capacity of the reservoir (m^3)

I = annual mean inflow into the reservoir (m^3)

t_s = average number of years during which the silt will fill up in a reservoir.

Practice in Pakistan

Presently, the life of the reservoir is being estimated as the number of years when the total capacity of the reservoir would be depleted by sediment and this has been obtained by dividing the capacity of the reservoir by the annual suspended sediment load passing at the site. Furthermore, it is also assumed that the dead storage would be depleted first and encroachment into live storage will start later.

DELTA FORMATION - ANALYTICAL AND MATHEMATICAL MODELS

DELTA FORMATION

The method of Borland and Miller as discussed in Chapter 6 gives the reduction in area and capacity of reservoir at different elevations, but it does not indicate the actual pattern of sediment deposit around the reservoir periphery and formulation of delta at the upstream end of reservoir i.e. the formation of bottom set, foreset and top set. Knowledge about delta formation is useful in case the intake for power or irrigation is much upstream from the dam. The deposit in delta can affect the entry of sediment into the intake as was the case at Upper Indravati Hydroelectric Project in Orissa. For such location of intake it is necessary to have some idea of delta formation.

The problem can be solved by (i) use of analytical methods and (ii) use of mathematical models.

ANALYTICAL MODELS

T.C. Menne and J.P. Kriel (1959)

They used limited data from a number of South African and American reservoirs to estimate slopes of sediment deposited in reservoir basins. Their graph gives the following relationship (Table 8.1).

Table 8.1 - Relationship between Sediment Slope and Shape Factor

Shape factor-length of reservoir/average width	Sediment slope as %age of original river bed slope	Shape factor	Sediment slope as %age of original river bed slope
4	75	20	38
5	68	30	33
6	65	50	27
8	57	70	23
10	52	10	20

This relationship, however, showed wide scatter of data. This is most probably due to the fact that the shape factor is a poor measure of average sediment carrying capacity in a reservoir.

W.M. Borland (1970)

The calculation procedure consists of firstly estimating the slope of the topset layers of the delta, whereafter the frontest slope is calculated by multiplying the former by a factor of 6.5. The topset slope is given by Borland on the basis of observation in 31 American reservoirs. He found that the ratio between the slope of deposited sediment and the original river bed slope varied between 1.0 and 0.2 Borland proposed a ratio of 0.5.

U.S.B.R. (1982)

The topset slope of the delta is fixed on the following considerations

(i) Statistical analysis of existing delta slopes of different reservoirs. This value is usually equal to one-half of the existing channel slope.

(ii) Meyer-Peter Muller's equation

The transport equation for zero bed load transport is given by:

$$S = \left[K.\ \frac{Q}{Q_B} \left(\frac{n_s}{D^{1/6}_{90}} \right)^{3/2} .\ D \right] / d \qquad 8.1$$

where

S = topset slope
K = coefficient equal to 0.19 (fps units) or 0.058 (metric units)
Q/Q_B = ratio of total flow in cfs (m^3/s) to flow over bed of stream in cfs (m^3/s). Discharge is referred to as dominant discharge and is usually determined by either channel bank full flow or as the mean annual flood peak.
D = diameter of bed material on topset slope usually determined as weighted mean diameter in mm
D_{90} = diameter of bed material for 90 percent finer than, mm
d = maximum channel depth at dominant discharge in ft (m)
n_s = Manning's roughness coefficient for the bed of channel sometimes computed as $D^{1/6}_{90}/26$

(iii) Schoklitsch formula for no bed load transport

$$S = \left(\frac{0.00021.D.B.}{Q} \right)^{3/4} \qquad 8.2$$

where

D = mean bed material particle size in mm D_5
B = stream width in ft
Q = mean annual flow discharge in cfs.

(iv) The average of foreset slopes observed in USBR reservoirs is 6.5 times the topset slope. However some reservoirs exhibit a foreset slope considerably greater than this i.e. Lake Mead foreset slope is 100 times the topset. By adopting a foreset slope of 6.5 times the topset, the first trial delta fit can be completed. The upstream end of the delta is set at the intersection of the maximum water surface and the streambed. The topset slope is projected from that point to the anticipated pivot point elevation to begin trial computations. If the volume of delta profile is found to be more than required, the topset slope is steepened and if the volume below the profile is found less than required, the topset slope is made flatter.

MATHEMATICAL MODELS

Models making use of sediment transport theories to simulate sediment distribution in reservoirs are those of Chang and Richards (1971), Yucel and Graf (1973), Asada (1973), Thomas (1977), Lopez (1978), White and Bettes (1984) and Pitt and Thompson (1984). The models of Chang and Richards (1971) and Yucel and Graf (1973) are both relatively simple and were only applied to hypothetical reservoirs represented by wide rectangular channels, whereas the models of Asada (1973), Thomas (1977), Lopez (1978), White and Bettes (1984) and Pitt and Thompson (1984) were used to simulate sediment deposition in real reservoir basins. Thomas (1977) is the author of the well known HEC-6 program of the U.S. Army Corps of Engineers. This program was improved upon by Binnie and Partners and was used in Tarbela reservoir (reported by Pitt and Thompson 1984). Several other mathematical models have been developed and are available to the users. Some work in this direction has also been done in India. Palaniappan (1991) has developed a model to determine aggradation and degradation in alluvival streams. Sharma (1995) has developed another elaborate model for the purpose. Most of the models adopt finite difference methods to solve the governing differential equations in an uncoupled system in these models, water surface profile is computed using standard step method. Sediment transport rates are calculated at all sections using the hydraulic characteristics computed at these sections. Bed load changes are computed from the differences in the sediment transport rates.

The HEC-6, ALLUVIAL, FLUVIAL 12, MOBED, HEC 2 SR, RESSED of Hydraulic Research Laboratory, Wallingford, SERES of Delft Hydraulic Laboratory, One Dimensional River Morphology (ODIRMO) and MIKE 11 are some of the models in use. The later three models viz. ODIRMO, FLUVIAL 12, and MIKE 11 solve the partial differential equations of water continuity, sediment continuity, momentum conservation of water and sediment motion equation by finite difference technique like Crank-Nicholson Scheme, Priessman Scheme, 6-point Abbot Scheme respectively. Solution of equation for the unknown is therefore adopted using Gaussian Elimination Method, Matrix Inversion Method or the Double Sweep Method. All the three models use the complete St.Venants' dynamic equation for momentum conservation. The sediment equations for transport and continuity are decoupled from the water equations of momentum and continuity.

These models use different sediment transport theories, the most common being Yang (1973); Ackers and White (1972); Engelund Hansen (1967); Rottner (1959); Laursen (1958); Einstein (1950); Graf and Acaroglu (1968); Bishop, Simons and Richardson (1965); Toffaletti (1968); Blench (1964); Kalinski (1947); Bagnold (1966); Yallin (1965); Dieegard and Fredson and that of L.C. van Rijn.

These models are mostly uni-dimensional which give aggradation or degradation of bed along longitudinal flow. However two-dimensional models have also been developed recently, which present a better picture of sedimentation.

The advantage of these models is that a clear picture is available of the possible sedimentation after a certain time run, say 25, 50, 100 years. The formation of delta is known and hence decision can be taken about the sill elevation of intake. However, the delta formation and sedimentation profile will depend upon the particular model used, the particular sediment transport equation chosen and the selection of model parameters like discharge and sediment boundaries. It is desirable to calibrate and prove the model with the existing data of aggradation and degradation.

REFERENCES

Annandale "Reservoir Sedimentation" Elsevier Amsterdam 1987.

Borland W.M. "Reservoir Sedimentation in River Catchments" (H.Shen Ed) Water Resources Publications, Fort Collins, Colorado, 1970.

Borland W.M. "Reservoir Sedimentation" Ch.29. "River Mechanics" Ed. H.W. Shen - Water Resources Publications Fort Collins Colorado 1971.

Borland W.M. and C.R. Miller "Distribution of Sediment in Large Reservoirs" Journal of the Hydraulics Divn. Proc. A.S.C.E. Vol. 84 1958 pp. 1587-1 to 1587-18.

Borland W.M. and T. Maddock "Sedimentation Studies for Planning of Reservoir by U.S.B.R." Proc. 4th Congress on Large Dams Report 411. New Delhi 1951.

Brown C.B. Discussion on "Sedimentation of Reservoirs" by B.J. Witzig Proc. A.S.C.E. Vol. 69 No. 6 1943. pp. 793-845 and 1493-1499.

Brown C.B. "Factors Affecting the Useful Life of Reservoirs". Jnl. of the Irrigation and Drainage Divn. A.S.C.E. Vol. 84 No. IR-1 January 1958.

Brune G.M. "Trap Efficiency of Reservoirs". Trans. Am. Geophysical Union Vol. 34. No. 3 June 1953 pp. 407-418.

Brune G.M. and R.E. Allen "A Consideration of Factors Influencing Reservoir Sedimentation in the Ohio Valley Region" Trans. Ame. Geo-physical Union. Vol. 22. pp. 649-655, 1958,

C.B.I. & P "Symposium on Silting of Reservoirs with Special Reference to Estimating the Life of Reservoirs and Measures to Arrest the Rate of Sedimentation". Publication No. 126 March 1977.

C.B.I. & P "Manual of River Behaviour, Control and Training" Revised Edition. Dr. D.V. Joglekar, Publication No. 60 Sept. 1971.

C.B.I. & P "Life of Reservoir" Technical Report No. 19. March 1977 and September 1980.

C.B.I. & P "Sedimentation Studies in Reservoirs" Technical Report No. 20. Vol. I September 1980 Vol. II January, 1981.

Chao P.C. and S. Ahmed "A Mathematical Model for Reservoir Sedimentation Planning" Water Power and Dam Construction January 1985 pp. 45-52.

Chen "Design of Sediment Retention Curve" Urban Hydrology and Sediment Control Symposium. Lexington U.S.A. 1975.

Churchil M.A. Discussion on "Analysis and Use of Reservoir Sedimentation Data" by L.C. Gottschalk. Proc. Federal Inter Agency Sedimentation Conference Colorado 1948 pp. 139-140 published by U.S.B.R.

C.W.C. "Compendium on study of Reservoirs in India" January 1991.

C.W.C. "Supplementary Lecture Notes and Country Papers of Regional Training Course on Reservoir Sedimentation and Control". Dec. 9-22. 1991. New Delhi.

Das G. "Run-off and Sediment Yield from Upper Ramganga Catchment". Ph.D Thesis in Agr. Eng. G.P. Pant University of Agriculture and Technology Pantnagar 1982.

Dhruv Narain and Ram Babu "Estimate of Soil Erosion in India". Jnl. Irrigation & Drainage Divn. A.S.C.E. Vol. 109 No. 3 1983.

Douglas I "Sediment Sources and Causes in the United Tropics of North-East Queensland in Harvey-Geomorphology in a Tropical Environment" British Geomorphological Research Group. Occasional Paper 5. pp. 27-39, 1968.

Flaxman E.M. "Some Variable which Influence Rates of Reservoir Sedimentation in Western USA" Symp. Lakes and Reservoirs. International Association of Science Hydrology 1966.

Garde R.J. et al "Mathematical Modelling of Sedimentation Processes in Reservoirs" Hydraulic Engg. Report. No. HYD. 8304. University of Roorkee 1983.

Garde R.J. and U.C. Kothyari "Sediment Erosion from Indian Catchments" 2nd International Workshop on Alluvial River Problems. Roorkee October 1985.

Garde R.J. and U.C. Kothyari "Erosion in Indian Catchments" Int. Symp. on River Sedimentation. Jackson (Mississippi). USA 1986.

Gill M.A. "Planning the Useful Life of a Reservoir" Water Power and Dam Construction. May 1988 pp. 46-47.

Gottschalk L.C. "Measurement of Sedimentation in Small Reservoirs" Trans. A.S.C.E. Vol. 117. pp. 59-71.

Graf W.H. "Storage Loses in Reservoirs". Water Power and Dam Construction. April 1984 pp. 37-40.

Guy H.P. and Ferguson G.E. "Sediment in Small Reservoirs due to Urbanisation" Paper No. 3070 Jnl. of Hyd. Divn. A.S.C.E. Vol. 88 Hyd. 2. March. 1962.

Heinemann H.G. "Sediment Distribution in Small Flood Retarding Reservoirs". U.S. Dept. Agr. ARS pp. 42-44. 1961.

Indian Standard I.S. 12182-1987. Guidelines for Determination of Effects of Sedimentation in Planning and Performance of Reservoirs.

Jiang Zhoushan and Song Wenjing "Sediment Yield in Small Watersheds in the Gullied - Hilley Loess Areas along the Middle Reaches of the Yellow River (In Chinese) Proc. International Symposium on River Sedimentation 1980 Vol. I pp. 63-72 - Quoted in WAPCOS Workshop on Sedimentation June 1991. New Delhi.

Joglekar D.V. "Silting of Reservoirs" Inst. of Engineers (India). Vol. XI. No. 8 Pt. I pp.527-530. April 1960.

Khosla A.N. "Silting of Reservoirs" C.B.I. & P Pub. No. 51., 153.

Kothyari U.C. et al "Analysis of Annual Rainfall" National Workshop on Flood Estimation in Himalayan Region (C.B. I&P) Roorkee September 1986.

Lal V.B. and S. Banerji "A Multivariate Prediction Equation for Rate of Sedimentation in North Indian Reservoirs". UNESCO. International Symposium on Interaction between Fresh Water and Sediment. Netherlands September, 1976.

Lane E.W. "Sediment Deposits in Flood Control and Multipurpose Reservoir" 4th Congress on Large Dams. New Delhi 1951.

Lane E.W. and V.A. Koelzer "Density of Sediments Deposited in Reservoirs" Rept. 9 in "A Study of Methods Used in the Measurements and Analysis of Sediment Loads in Streams". U.S. Corps of Engineers. St. Paul District Sub-office. Hydraulic Laboratory University of Iowa city. Iowa 1943.

Lara J.M. "Revision of Procedure to Compute Sediment Distribution in Large Reservoirs". U.S.B.R. Hydrology May 1962.

Maddock T. and W.M. Borland "Sedimentation Studies for the Planning of Reservoirs by the Bureau of Reclamation" 4th ICOLD. Congress New Delhi 1951 Q.14. R. 41.

Menne T.C. and J.P. Kriel "Determination of sediment loads in rivers and deposition of sediment in storage reservoirs" Technical Report No. 3. Dept. of Water, South Africa, 1959.

Miller C.R. "Determination of Unit Weight of Sediment for Use in Sediment Volume Computations" U.S.B.R. Project Planning Divn. Memo 1953.

Ministry of Agriculture, Govt. of India, Soil Conservation Divn. Central Unit for Soil Conservation (Hydrology and Sedimentation). "Handbook of Sedimentation" New Delhi. July 1972.

Mon Zinz et al "Prediction of Sediment Yield and Evaluation of Silt Detention by Measures of Soil Conservation with Small Watersheds on North Shaanxi (In Chinese)". Proc. International Symposium on River Sedimentation 1980 Vol. I pp. 73-82-Quoted in WAPCOS Workshop on Sedimentation June 1991 New Delhi.

Moore Charles M; W.J. Wood and G.W. Renfro "Trap Efficiency of Reservoirs, Debris Basins and Debris Dams". Proc. ASCE Air Transport Division, Paper No. 2374. February 1960 pp. 69-87.

Musgrave G.W. The Quantitative Evaluation of Factors in Water Erosion; a First Approximation". Jnl. Soil Water Conservation Vol. 2. No. 3. pp. 133-138. July. 1947.

National Institute of Hydrology "Study of Soil Erosion from Different Land Uses and Vegetal Covers Using Universal Soil Loss Equation" TR 28. 1986-87 Roorkee.

Pemberton E. "Survey and Prediction of Sedimentation in Reservoirs". Book "Application of Stochoastic Processes in Sediment Transport" Edited by H. Shen et al; Water Res. Publ. Littleton Colorado U.S.A. 1980.

Satish Chandra "Assessment of Water Erosion and Sediment Transport" International Symposium on "Water Erosion Sedimentation and Resource Conservation" October 9-13, 1990 Dehradun.

Shangle, A.K. "Reservoir Sedimentation - Status - in - India". Jalvigyan Sameeksha. N.I.H. Roorkee. Vol. V December 1991.

Smith D.D. "Interpretation of Soil Conservation Data for Field Use". Agr. Eng. 2-pp.173-175.

Szechowycz R.M. and M.M. Qureshi "Sedimentation in Mangla Reservoir". Paper No. 10033. Jnl. of the Hyd. Divn. A.S.C.E. Vol. 99. No. Hy. 9. Sept. 1973.

U.P.I.R.I. "Final Report on Sedimentation Studies in Streams and Reservoirs". T.M. No. 45. R.R. (H_1-7). Roorkee March 1975.

U.S.B.R. "Reservoir Sedimentation" Technical Guidelines, October 1982, by Robert I. Strand and Ernest L. Pemberton.

Varshney R.S. "Regional Sedimentation Curves for India". Indian Jnl. of Power and River Valley Development pp. 357-379. Sept. 1990.

Varshney R.S. "Engineering Hydrology" Ch. 20 Third Edition. 1986. M/s Nem Chand & Bros. Roorkee.

Varshney R.S. et. al. "Variation of Sediment Rate of Reservoirs in Himalayan Regions with Catchment". 53rd Annual Research Session of C.B. I. & P Vol. II May 8-10. 1986. Bhubaneshwar.

Ven-te-Chow (Ed) "Handbook of Applied Hydrology" McGraw-Hill Book Co. New York 1964-Ch. 17 by L.C. Gottschalk.

WAPCOS India "Workshop on Management of Reservoir Sedimentation". 27-30 June 1951 New Delhi.

William J.R. "Sediment Yield Prediction with Universal Equation Using Runoff Energy Factor in Present and Prospective Technology for Predicting Sediment Yields and Sources" ARS - S - 40 USDA Agriculture Research Service pp. 244-252.

Zingg A.W. Degree and Length of Land Slope as it Effects Soil Loss in Runoff. Agr. Eng. 21 pp. 59-64.

STATEMENT SHOWING THE DATA IN RESPECT OF 32 RESERVOIRS HAVING GROSS CAPACITY 0.062 MILLION HA M (0.5 MILLION ACRE-FT) AND ABOVE IN INDIA.

Sl. No.	Name of Dam	Location: River	Location: Nearest City	Location: State	Height: Above Lowest Foun-dation (M)	Height: Above Ground Level (M)	Length of Crest (M)	Gross Capacity of Reservoir: (10^6m^3)	Gross Capacity of Reservoir: (Acre-ft)	Dead storage	Live storage	Method adopted in calculating the Life of Reservoirs
1	2	3	4	5	6	7	8	9	10	11	12	13
1.	Nagarjunasagar	Krishna	Macherla	Andhra Pradesh	123.7	112.77	4650.0	11,315.4	9177000	476.1	6919.8	No method has been adopted for calculating the life of reservoir. However, the life of reservor haas been estimated to be 377 years.
2.	Srisailam	Krishna	Hyderabad	Andhra Pradesh	143.2	12.9	512.0	8723.0	7072000	2766.0	5958.0	Based on the silt observations in past on River Krishna the life of reservoir has been worked out to 450 years.
3.	Nizamsagar	Manjira	Nizamabad	Andhra Pradesh	-	-	-	715	580000	94	485	Not available
4.	Pochampad	Godavari	Nirmal Taluk	Andhra Pradesh	43.5	-	-	3170	2570000	-	2319	Not available
5.	Machkund	Machkund	Jalpat	Andhra Pradesh	50.6	-	409.6	770	624000	-	752	Not available
6.	Panchet	Damodar	Distt. Dhanbad	Bihar	40.81C 40.84E	-	-	1497	1210000	-	1307	Not available
7.	Maithon	Barakar	Asansol	Bihar	56.0	50.0	4847.0	820.0	664800	207.2	6118.2	For the purpose of estimating life of reservoir the dead storage capacity is divided by quantity of silt annually deposited 84.13 ha m (684 acre-ft). The estimated life of reservoir is 246 years.
8.	Kadana	Mahi	Santrampur	Gujarat	58.0	24.0	1398.0	1714.2	1388502	339.6	1202.7	Moody's modified empirical area reduction method has been used. The life of reservoir has been worked out as 100 years.
9.	Ukai	Tapti	Surat	Gujarat	68.6E	68.6E	4927.0	8511.0	6900000	1171.8	7462.6	Assuming that half of the total silt, i.e., 1778.22 ha m(14457.1 acre-ft) (average observed at Kakrapar for 3 years) is carried away along with floods passing over the spillway and through the undersluices, the sedimentation rate works out to 0.014 ha m/sq km (0.31 acre-ft/sq mile) per year. For catchment area of 60515.11 sq km (23,365 sq miles), the life of reservoir is estimated to be 131.5 years with a silt reserve of 0.117 million ha m (0.95 million acre-ft).

Impact of Siltation on the Useful Life of Large Reservoirs

1	2	3	4	5	6	7	8	9	10	11	12	13
10.	Vanivilas Sagar	Vedavati	Chitaldurg	Karnataka	49.8	43.3	405.4	849.6	688705	38.2	812.9	Not available
11.	Krishnarajasagar	Cauvery	Mysore	Karnataka	42.7	39.6	2621.3	1368.7	1100000	123.4	1247.0	Not available
12.	Tungabhadra	Tungabhadra	Hospet	Karnataka	49.4	35.35	2440.2	4040.0	305400	442.8	33304	Based on the observation of two anicuts above the dam site, the yearly silt deposit has been estimated at 3.64 million cu m (128.6 million cu ft), ie 363.81 ha m (2957.8 acre-ft). On this basis life of reservoir as a whole will be several hundred years.
13.	Bhadra	Bhadra	Shimoga	Karnataka	71.6	59.1	1190.2	2022.0	1641640	236.8	1788.6	Not available
14.	Almatti	Krishna	Bijapur	Karnataka	38.7	34.7	457.2	2348.2	1905000	-	-	The rate of silting is worked out by empirical formula given by Inglis ($S=cm^{3/4}$) and thus life of reservoir has been worked out as 122 years.
15.	Hidkal	Ghataprabha	Belgaum	Karnataka	59.4	43.9	4267.2	1455.5	1179390	45.3	-	The average annual silt load of 0.42 million cu m (15.00 million cu ft) per year has been considered by using empirical formula, viz, Inglis and Khosla's formulae. The life of reservoir has been worked out as 100 years.
16.	Siddapur	Krishna	Bijapur	Karnataka	25.5	23.6	512.0	790.4	641200	-	-	Not available
17.	Linganamakki	Sharavathi	Shimoga	Karnataka	61.3	55.2	2.62	4417.0	5582000	141.8	4276.5	Based on Khosla's formula for silting, i.e., 0.035 ha m/sq km (0.75 acre-ft per sq mile) per year, for catchment area of 1991.70 sq km (769 sq miles) the dead storage provided will give life of 200 years.
18.	Malaprabha	Malaprabha	Dharwar	Karnataka	43.3	37.2	154.0	879.8	713300	93.9	-	Assuming the rate of silting as 3.56 ha m/year/100 sq km (75 acre- ft/year/100 sq miles) for catchment according to Khosla's and Inglis formulae. A provision of 100 years silt load has been made.
19.	Hemavathi	-	-	Karnataka	-	-	-	654	530000	-	-	Not available
20.	Ghataprabha	Ghataprabha	Belgaum	Karnataka	45.00	-	1300	661	540000	-	618	Dead storage designed on the basis of Khosla's formula of 3.75 ha m/100 sq km (75 acre-ft/100 sq miles) gives annual silt load of 42.4 ha m (345 acre-ft) for a period of 100 years.
21.	Idikki	Periyar	Thodupauzha	Kerala	171.0	168.0	366.0	1459.53	1182219	-	-	Not available

Impact of Siltation on the Useful Life of Large Reservoirs

1	2	3	4	5	6	7	8	9	10	11	12	13
22.	Bhatghar	Yalvandi	Bhor	Maharashtra	59.0	51.2	1625.0	682.6	552900	-	-	Not available
23.	Mulshi	Mula	Poona	Maharashtra	50.6	44 5	1555.4	761.1	611300	217.1	536.6	Not available
24.	Koyna(Shivaji	Koyna	Karad	Maharashtra	103.0	-	804.6	2780.0	2250000	141.9	2499.0	Some silt data werecollected in Koyna River during monsoon of 1949 but this was not considered conclusive. Some similar data were collected for Khadakwasla reservoir near Poona. This reservoir has a catchment similar to the Koyna and the results are to some extent applicable. Judged by these two observations it is anticipated that the probable annual silt load in Koyna reservoir would be of the order of 5.034 to 7.88 ha m/100 sq km/year (106 to 166 acre-ft per 100 sq miles/year). These figures are much higher than Shri Khosla's. It is, therefore, expected that the silting life of the reservoir as far as drawn off for power is concerned, will not be less than 150-200 years.
25.	Bhima	Bhima	Madha Taluk (Sholapur)	Maharashtra	43.28	-	2330	3040	2470000	-	1342	Not available
26.	Juyakawadlai	Godavari	Maition	Maharashtra	35.50	-	-	1456	1177000	-	1036	Not available
27.	Warna	Warna	Shirla	Maharashtra	58.83	-	-	2442	1980000	-	1036	Not available
28.	Girna	Girna	Nasik	Maharashtra	53.3	40.5	964.0	678.0	549600	28.4	652.1	Dead storage designed for a silt rate of 0.0056 ha m/sq km/ year (0.12 acre-ft/sq mile/year) for life of 100 years.
29.	Mula	Mula	Ahmednagar	Maharashtra	55.5	50.5	2820.0	1017.0	824500	131.9	604.4	Rate of silting has been taken as 0.035 ha m/sq km/year (0.75 acre-ft per sq mile/year)
30.	Yeldari	Purna	Prabhani	Maharashtra	51.40	42.70	3270.0	964.0	781600	152.9	811.6	Dead storage designed for a silt rate of 2/3, i.e., 0.031 ha m/sq km/year (0.66 acre-ft/sq mile/year) for a life of 75 years.
31.	Gandhisagar	Chambai	Jhalawar	Madhya Pradesh	-	62.2	513.6	8450.0	6850000	832.6	6911.2	Dead storage has been provided on the basis of Shri Khosla's recommendation, viz., a silt reserve of 0.035 ha m/sq km (0.75 acre-ft per sq mile) of catchment per year for 100 years.
32.	Tawa	Tawa	Hoshangabad	Madhya Pradesh	55.2	-	1330	3645	2955000	-	2764	Not available

Impact of Siltation on the Useful Life of Large Reservoirs

1	2	3	4	5	6	7	8	9	10	11	12	13
33.	Jalaput	Machkund	Vishakhapatnam	Orissa/ Andhra Pradesh	55.5	44.8	634.0	970.5	786800	-	-	-
34.	Balimela	Sileru	Jeypore	Orissa	70.0	-	4633.0	3823.0	3096630	-	-	Not available
35.	Hirakud	Mahanadi	Sambalpur	Orissa	58.2G +61.3E	43.3G 61.3E	1148.5 +3651.5E	8141.0	6600000	2319.0	5822.0	The life of the reservoir has beer originally worked out on the basis of theory of deltaic formation. For this purpose the bed widtl of the stablished river has been taken as 0.80 km (1/2 mile), th critical slope as 1/4000 and th coefficient rugosity as 0.025. The critical discharge to establish a regime has been taken a 11326.72 cumecs (400000 cusecs).
36.	Bhkara (Govindsagar)	Sutlej	Chandigarh	Punjab	225.6	167.6	518.2	9868.0	8000000	2053.7	7814.1	For Bhakra Reservoir, the sediment (Govindsagar) volume has been compute on the basis of densities of 1041 kg/ cu m and 1441.8 kg/cu r (65 lb/cu ft and 90 lb/cu f separately and average value have been taken to represent th volume of silt brought into th reservoir annually. This annum incoming silt has been workdout at 3936.0 ha m (32,00 acre-ft) respectively for assume densities. The average of the volumes, 3382.5 ha m (27,50 acre-ft) has been taken to represent the annual incoming si. This gives a rate of 0.013 cu r sq km (1.2 cu ft/sq miles) per year.
37.	Beas	Beas	Talwara Township	Punjab	115.8	100.6	1524.0	8140.0	6600000	-	7290.0	Mile by mile capacity method at Moody's modified empirical are reduction method have been us and it is estimated that abc 15 percent of dead storage a 18 percent of live storage a 18 percent of live storage m cost in 100 years.
38.	Ranapratap Sagar	Chambal	Kota	Rajasthan	54.0	39.2	1144.0	2890.0	2340000	764.8	2133.9	Based on Shri Khosla's form of 0.035 ha m per 100 sq/year (0.75) acre-ft per 100 sq miles/year).
39.	Bajajsagar	Mahi	Banswara	Rajasthan	74.0	62.5	944.9	2038.8	1653000	345.0	1715.0	Moody's modified empirical a reduction method has been us. The life of reservoir has be worked out as 100 years.
40.	Mettur (Stanley Dam)	Cauvery	Salam	Tamil Nadu	64.9	53.6	1615.4	2708.0	2197000	62.9	2647.0	Not available
41.	Lower Bhawani	Bhawani	Mettupalayam	Tamil Nadu	67.18	42.67G	8791.0	792.8	642880	0.4	930.0	Not available

Impact of Siltation on the Useful Life of Large Reservoirs

1	2	3	4	5	6	7	8	9	10	11	12	13
42.	Rihand (Govind Balabpant Sangar)	Rihand	Mirzapur	Uttar Pradesh	92.9	80.5	934.2	10630.0	8600000	1726.9	9214.1	Assuming silt deposit of 1/500 (this corresponds to some thing like 1/800 as per Khosla's formula of 0.092 ha m/year (0.75 acre-ft/year) of the average annual runoff and taking life of reservoirs as 100 years provisions necessary to silting amounts to 0.169 million ha m (1.38 million acre-ft) as against 0.172 million ha m (1.4 million acre-ft) provided. Balabpant Sagar)
43.	Matatila	Betwa	Jhanshi	Uttar Pradesh	36.6	24.4	6315.5	1132.3	918000	111.0	874.5	In the project report of 1951, provision was made for dead storage for 100 years at the rate of 0.013 million cu m/sq km (1.2 million cu ft per sq mile) for 100 years (on the basis of rate of silting observed at Dhukwan). In the later revised project report this has been reduced to 92.85 M cu m (3279 million cu ft) on 927629 ha m (75147 acre-ft) which is nearly 1/3 of the first provision). This dead storage provision is also reduced for 30 years instead of 100 years. The new assumption made is that 30 percent of the silt will get deposited in the silt pocket and the remaining silt will get deposited in the live storage.
44.	Ramganga	Ramganga	Dhampur	Uttar Pradesh	125.6	108.8	557.8	2369.3	1920000	2467	1948.9	Based on silt load data collected for other reservoirs like Bhakra Hlrakud, etc., a silting rate of 4.27 ha m/100 sq km (90 acre-ft/100 sq miles) gives like of 185 years before reservoir will get silted up to dead storage elevation.
45.	Canada(Masanjor)	Mayurakshi	Dumka	West Bengal	47.2	37.5	640.0	616.7	500000	67.8	540.3	Some rough silt experience were made at the site of the dam during 1937 and 1938. the average quantity of silt in river discharge during floods in these years is found to be 0.028 cu m in 33.98 cu m (1 cu ft in 1200 cu ft) of water. During 1939-40 silt observations were carried out on scientific basis from July to September and the average proportion of silt is 0.114 percent or part in 900 parts [0.92 million cu m (34 million cu ft)]. Taking this rate of silting life has been calculated as 200 years.
46.	Kangsabati	Kangsabati	Bankura	West Bengal	41.0	38.0	10400.0	1135.0	920000	145.5	989.2	A silting rate of 0.07 ha am/sq km (1.50 acre-ft/sq mile) per yer for 100 years has been assumed.

CONSTITUTION OF INDIAN NATIONAL COMMITTEE ON HYDROLOGY

i.	Chairman Central Water Commission, New Delhi	Chairman
ii.	Director National Institute of Hydrology, Roorkee	Executive Member
iii.	Dy. Director-General Geological Survey of India, Calcutta	Member
iv.	Chairman Central Ground Water Board, Faridabad	Member
v.	Dy.Director-General India Meteorological Department, New Delhi	Member
vi.	A Senior Scientist National Remote Sensing Agency, Hyderabad	Member
vii.	Member (D&R) Central Water Commission, New Delhi	Member
viii.	Director Research, Designs & Standards Organization, Lucknow	Member
ix.	Additional Director Indian Institute of Tropical Meteorology, Pune	Member
x.	Director, Central Designs Organization, Gujarat, Gandhinagar	Member
xi.	Chief Engineer (Design) Irrigation Department, U.P. Roorkee	Member
xii.	Director, Central Designs Organization, West Bengal, Calcutta	Member
xiii.	Director, BODHI, MP Bhopal	Member
xiv.	Chief Engineer & Director Water Resources Development Organization, Karnataka Bangalore	Member
xv.	Chief Engineer, Central Designs Organization, Maharashtra, Nasik	Member
xvi.	Dr. B.V. Rao, Indian Institute of Technology, Bombay	Member
xvii.	Dr. T. Prasad, Director Centre for Water Resources Studies, Bihar College of Engineering, Patna	Member
xviii.	Dr. N.V. Pandarikanthan Director, Centre for Water Resources, Anna University Madras	Member
xix.	President, Indian Association of Hydrologists, Roorkee	Member
xx.	Director (R&D&SA) Central Water Commission, New Delhi	Member
xxi.	Senior Scientist National Institute of Hydrology, Roorkee	Member-Secretary