Chapter TWO_PART2

STORAGE, PONDAGE AND FLOW DURATION CURVES

10.1 RESERVOIR MASS CURVE AND STORAGE

During high flows, water flowing in a river has to be stored so that a uniform supply of water can be assured, for water resources utilisation like irrigation, water supply, power generation, etc. during periods of low flows of the river.

A mass diagram is a graphical representation of cumulative inflow into the reservoir versus time which may be monthly or yearly. A mass curve is shown in Fig. 10.1 for a 2-year period. The slope of the mass curve at any point is a measure of the inflow rate at that time. Required rates of draw off from the reservoir are marked by drawing tangents, having slopes equal to the demand rates, at the highest points of the mass curve. The maximum departure between the demand line and the mass curve represents the storage capacity of the reservoir required to meet the demand. A demand line must intersect the mass curve when extended forward, otherwise the reservoir is not going to refill. The vertical distance between the successive tangents represent the water wasted over the spillway. The salient features in the mass curve of flow in Fig. 10.1 are:

- *a-b*: inflow rate exceeds the demand rate of x cumec and reservoir is overflowing
- *b*: inflow rate equals demand rate and the reservoir is just full
- *b-c*: inflow rate is less than the demand rate and the water is drawn from storage
- *c*: inflow rate equals demand rate and S_1 is the draw off from the reservoir (Mm^3)
- *c-d*: inflow rate exceeds demand rate and the reservoir is filling
- *d*: reservoir is full again
- *d-e*: same as *a-b*
- *e*: similar to *b*
- *e-f*: similar to *b-c*
- *f*: inflow rate equals demand rate and S_2 is the draw off from the reservoir
- *f-g*: similar to *c-d*

To meet the demand rate of x cumec the departure $S_2 > S_1$; hence, the storage capacity of the reservoir is S_2 Mm^3. If the storage capacity of the reservoir, from economic considerations, is kept as S_1 Mm^3, the demand rate of x cumec can not be maintained during the time *e-f* and it can be at a lesser rate of y cumec ($y < x$).

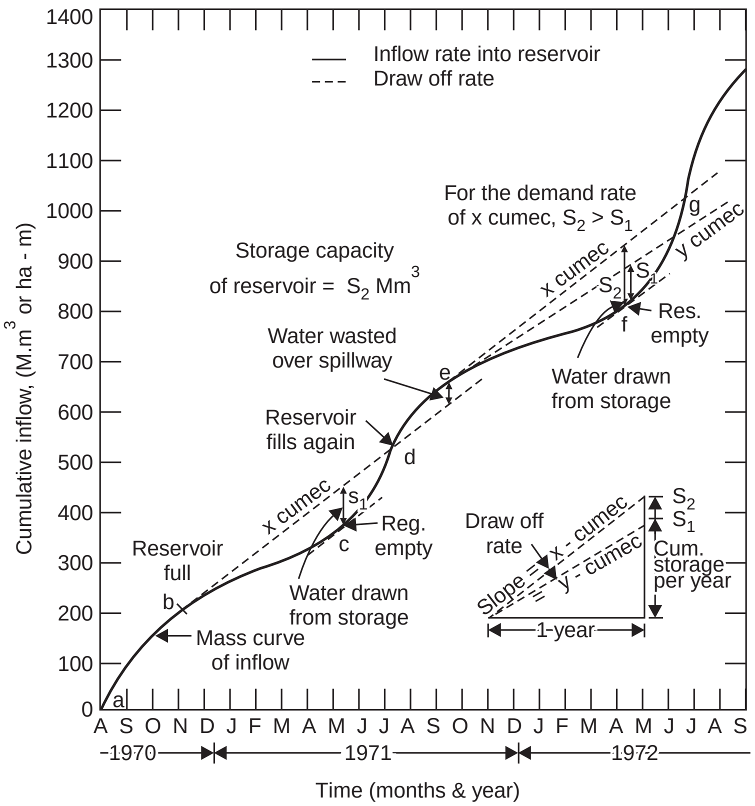

Fig. 10.1 Storage capacity of reservoir from mass curve

The use of mass curve is to determine:

(*i*) the storage capacity of the reservoir required to meet a particular withdrawal rate.

(*ii*) the possible rate of withdrawal from a reservoir of specified storage capacity.

The observed inflow rates have to be adjusted for the monthly evaporation from the reservoir surface, precipitation, seepage through the dam, inflow from adjacent basins, required releases for downstream users, sediment inflow, etc. while calculating the storage capacity of the reservoir.

The average flow figures for the site of a proposed dam are collected for about 10 years. From this record the flow figures for the driest year are used for drawing the mass flow curve. Graphical analysis is enough for preliminary studies. Final studies are made by tabular computation. If tangents are drawn to the crest and trough of the mass curve such that the departure of the lines represents the specified reservoir capacity, the slope of the tangent at the crest gives the continuous flow that can be maintained with the available storage capacity. From this the greatest continuous power output for the available fall at the site for a given plant efficiency and load factor can be determined.

From the daily flow data a hydrograph or a bar graph is drawn for the maximum flood during the period of 10 years and the spillway capacity to pass this flood with the available storage capacity is determined. Thus, the power and the flood control potentialities of the site are investigated. Also see Appendix-C.

The mass curve of water utilisation need not be a straight line. The dashed curve in Fig. 10.2 shows the cumulative requirements of water use in different months as compared with monthly cumulatively inflow. The maximum draft in the reservoir (*i.e.,* maximum departure of the water use and inflow curves) occurs by the end of April. The reservoir again becomes full by the end of September when the two curves intersect.

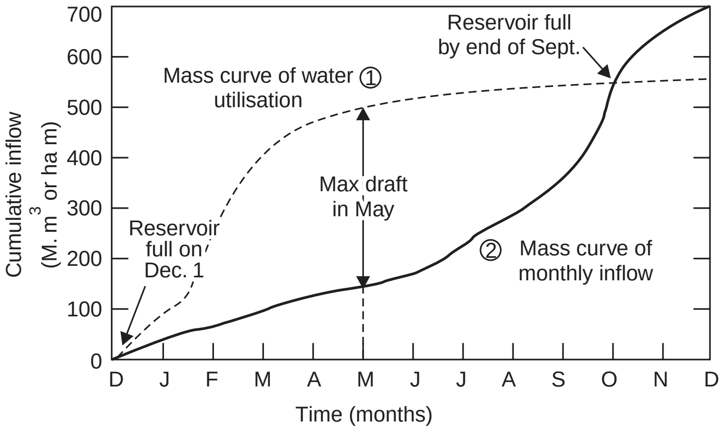

Fig. 10.2 Mass curves of water utilisation and monthly inflow

Example 10.1 *The following is a record of the mean monthly discharges of a river in a dry year. The available fall is 80 m. Determine*

(*i*) *the minimum capacity of a reservoir if the entire annual inflow is to be drawn off at a uniform rate* (*with no flow going into waste over the spillway*).

(*ii*) *the amount of water which must be initially stored to maintain the uniform draw off.*

(*iii*) *the uniform power output assuming a plant efficiency of 70%.*

(*iv*) *If the amount of water initially stored is 125 Mm^3, the maximum possible draw off rate and the amount of water wasted over the spillway* (*assuming the same reservoir capacity determined in* (*i*) *above.*

(*v*) *if the largest reservoir that can be economically constructed is of capacity 125 Mm^3, the maximum possible output and the amount of water wasted over the spillway.*

(*vi*) *the capacity of the reservoir to produce 22.5 megawatts continuously throughout the year.*

Month	*Mean flow (cumec)*	*Month*	*Mean flow (cumec)*
Jan.	29.7	July	68.0
Feb.	75.3	Aug.	50.2
March	66.8	Sept.	74.5
April	57.2	Oct.	66.8
May	23.2	Nov.	40.5
June	26.3	Dec.	26.3

Solution Take each month as 30 days for convenience; 1 month = 30 days × 86400 sec = 2.592 × 10^6 sec. Inflow volume in each month = monthly discharge × 2.592 Mm^3; and monthly inflow and cumulative inflow are tabulated in Table 10.1.

Table 10.1 Cumulative inflow into reservoir

Month	*Mean flow (cumec)*	*Inflow volume (Mm^3)*	*cumulative inflow (Mm^3)*	*Month*	*Mean flow (cumec)*	*Inflow volume (Mm^3)*	*cumulative inflow (Mm^3)*
Jan.	29.7	77	77	July	68.0	176	897
Feb.	75.3	195	272	Aug.	50.2	130	1027
Mar.	66.8	173	445	Sept.	74.5	193	1220
April	57.2	148	593	Oct.	66.8	173	1393
May	23.2	60	653	Nov.	40.5	105	1498
June	26.3	68	721	Dec.	26.3	68	1566

Plot the mass curve of flow as cumulative inflow vs month as shown in Fig. 10.3.

(*i*) Join *OA* by a straight line; the slope of *OA*, *i.e.*, 1566 Mm^3/yr or (1566 × 10^6)m^3/(365 × 86400) sec = 49.7 cumec is the uniform draw off throughout the year with no spill over the spillway. Draw *BC* ‖ *OA*, *GH* ‖ *OA*, *B*, *G* being the crests of the mass curve; *EH* = *FG*

Minimum capacity of reservoir = *DE* + *EH* = 150 + 20 = **170 Mm^3**

Note If the capacity is less than this, some water will be wasted and if it is more than this, the reservoir will never get filled up.

(*ii*) Amount of water to be initially stored for the uniform draw off of 49.7 cumec = *DE* = **150 Mm^3**

(*iii*) Continuous uniform power output in kW, $P = \dfrac{\rho_w g\, QH}{1000} \times \eta_0$

where ρ_w = mass density of water, 1000 kg/m^3

Q = discharge into turbines

H = head on turbines (≈ available fall)

η_0 = overall or plant efficiency

$$\therefore \quad P = \frac{1000 \times 9.81 \times 49.7 \times 80}{1000} \times 0.70$$

$$= 27400 \text{ kW}$$

or $$= \mathbf{27.4\ MW}$$

(*iv*) If the amount of water initially stored is only 125 M.m^3, measure *DI* = 125 M.m^3, join *BI* and produce to *J*. The slope of the line *BJ* is the maximum possible draw off rate. Let the line *BJ* intersect the ordinate through *O* (*i.e.*, the cumulative inflow axis) at *K*. The vertical intercept *KJ′* = 1430 Mm^3 and the slope of this line = 1430 Mm^3/yr = 45.4 cumec which is the maximum possible draw off rate.

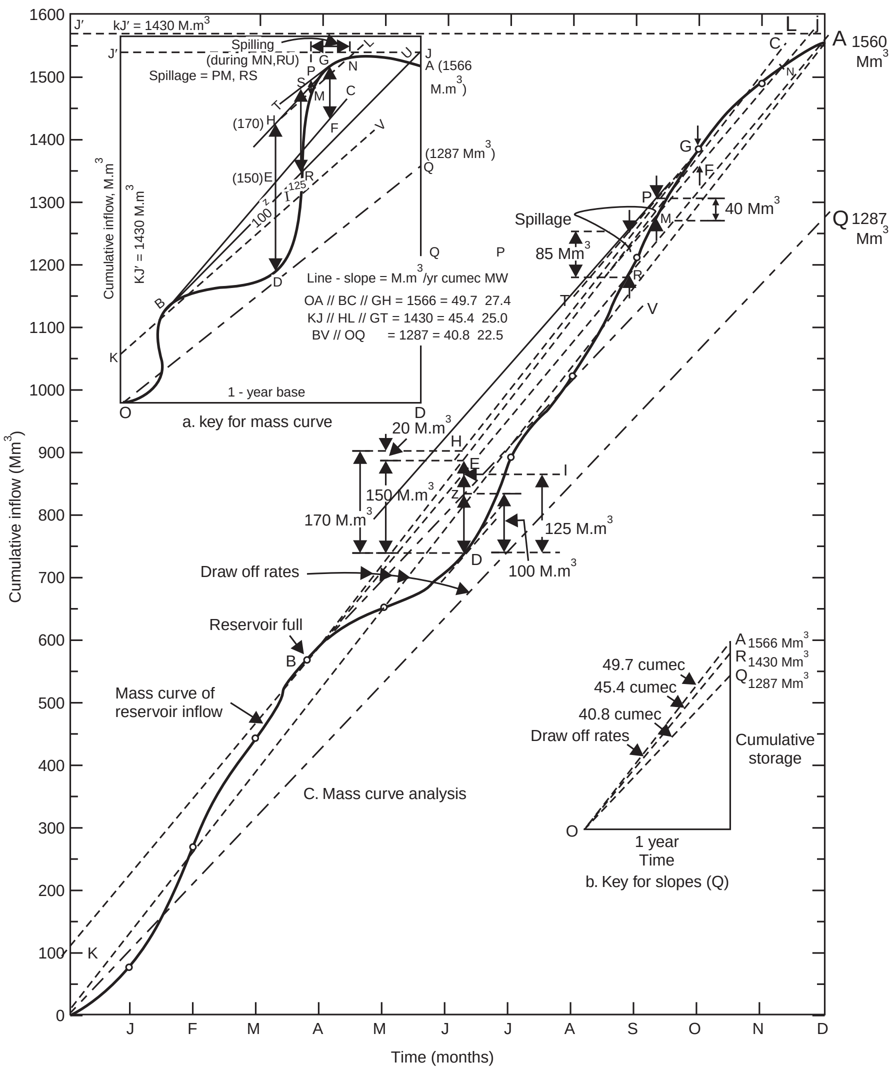

Fig. 10.3 Mass curve studies in reservoir design (Example 10.1)

To maintain the same reservoir capacity of 170 M.m^3, draw the straight line $HL \parallel KJ$ intersecting the mass curve of flow at M and N. Draw the straight line $GT \parallel HL$. The vertical intercept PM gives the amount of water wasted over the spillway (during the time period MN) which is 40 Mm^3.

(v) If the reservoir capacity is limited to 125 M.m^3 from economic considerations, the line KJ intersects the mass curve of flow at R. Let the vertical at R meet the line GT ($GT \parallel KJ$) at S. In this case the amount of water wasted over the spillway = RS = 85 Mm^3. The maximum possible output in this case for a uniform draw off rate of 45.4 cumec is

$$P' = 27.4 \times \frac{45.4}{49.7} = \mathbf{25\ MW}$$

(*vi*) For a continuous power output of 22.5 MW the uniform draw off rate can be determined from the equation

$$22500 \text{ kW} = \frac{1000 \times 9.81 \times Q \times 80}{1000} \times 0.70$$

$$Q = 40.8 \text{ cumec}$$

which can also be calculated as $49.7 \times \frac{22.5}{27.4} = 40.8$ cumec = 40.8 (365 × 86400 sec) = 1287 Mm^3/yr.

On the 1-year base, draw the ordinate at the end of December = 1287 $M.m^3$ and join the line *OQ* (dashed line). The slope of this line gives the required draw off rate (40.8 cumec) to produce a uniform power output of 22.5 mW. Through *B* and *D, i.e.,* the crest and the trough draw tangents parallel to the dashed line *OQ* (*BV* ‖ *OQ*). The vertical intercept between the two tangents *DZ* gives the required capacity of the reservoir as 100 Mm^3.

10.2 FLOW DURATION CURVES

Flow duration curves show the percentage of time that certain values of discharge weekly, monthly or yearly were equalled or exceeded in the available number of years of record. The selection of the time interval depends on the purpose of the study. As the time interval increases the range of the curve decreases, Fig. 10.4. While daily flow rates of small storms are useful for the pondage studies in a runoff river power development plant, monthly flow rates for a number of years are useful in power development plants from a large storage reservoir. The flow duration curve is actually a river discharge frequency curve and longer the period of record, more accurate is the indication of the long term yield of a stream. A flat curve indicates a river with a few floods with large ground water contribution, while a steep curve indicates frequent floods and dry periods with little ground water contribution. Since the area under the curve represents the volume of flow, the storage will affect the flow duration curve as shown by the dashed line in Fig. 10.5; *i.e.,* reducing the extreme flows and increasing the very low flows.

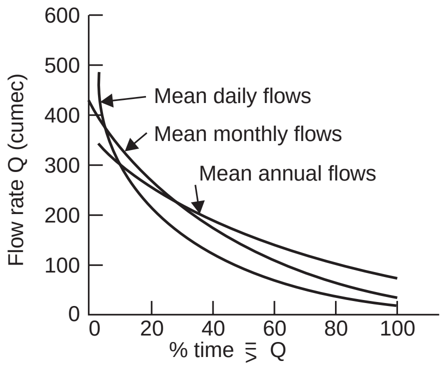

Fig. 10.4 Flow duration curves—effect of observation period

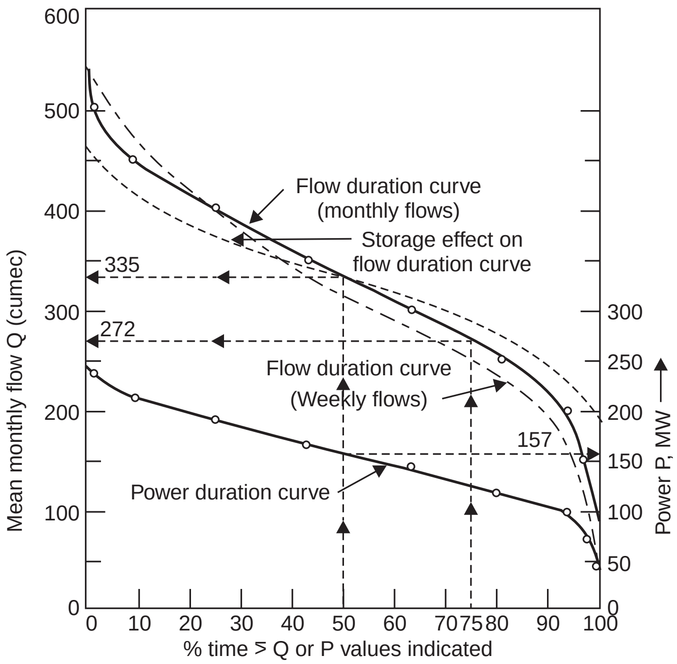

Fig. 10.5 Flow duration and power duration curves (Example 10.2)

Since drought is often defined in terms of a fixed period of time with less than some minimum amount of rainfall, the flow duration curves are useful for determining the duration of floods or droughts, the latter being of prime importance in the semi-arid regions. Duration curves for long periods of runoff are also useful for deciding the flow rates to be used for particular purposes, say, for power development.

The usual procedure is to arrange the flow values (or range of flow values weekly, monthly or yearly) in the available period of record (usually a minimum of 10 years) in the ascending order of magnitude and the number of occurrences of each flow value (or range of flow values). From this the number of times and the percent of time each flow value (or range of flow values) has been equalled or exceeded in the period of record may be obtained. The duration curve is constructed by plotting each flow value (or lower value of the class interval) against the percent of time it has been equalled or exceeded. The power duration curve is the same as the flow duration curve, the discharge scale being converted to power units corresponding to the available head (assuming the head constant) since

Power in kW, $$P = \frac{\rho_w g\, QH}{1000} \times \eta_0$$

or, $$P = \text{a constant} \times Q$$

where Q is the flow value being equalled or exceeded during a certain percent of time.

Flow duration curves are useful in the studies relating to navigation problems, water power, water supply, irrigation and sanitation.

Example 10.2 *The following data are obtained from the records of the mean monthly flows of a river for 10 years. The head available at the site of the power plant is 60 m and the plant efficiency is 80%.*

Mean monthly flow range (cumec)	*No. of occurrences (in 10-yr period)*
100-149	3
150-199	4
200-249	16
250-299	21
300-349	24
350-399	21
400-499	20
450-499	9
500-549	2

(*a*) *Plot*

(*i*) *The flow duration curve* (*ii*) *The power duration curve*

(*b*) *Determine the mean monthly flow that can be expected and the average power that can be developed.*

(*c*) *Indicate the effect of storage on the flow duration curve obtained.*

(*d*) *What would be the trend of the curve if the mean weekly flow data are used instead of monthly flows.*

Solution (*a*) The mean monthly flow ranges are arranged in the ascending order as shown in Table 10.2. The number of times that each mean monthly flow range (class interval, C.I.) has been equalled or exceeded (m) is worked out as cumulative number of occurrences starting from the bottom of the column of number of occurrences, since the C.I. of the monthly flows, are arranged in the ascending order of magnitude. It should be noted that the flow values are arranged in the ascending order of magnitude in the flow duration analysis, since the minimum

Table 10.2 Flow duration analysis of mean monthly flow data of a river in a 10 yr period (Example 10.2)

Mean monthly flow class interval C.I. (cumec)	*No. of occurrences (in 10-yr period)*	*No. of time equalled or exceeded (m)*	*Percent of time lower value of CI equalled or exceeded* $= \frac{m}{n} \times 100\%$	*Monthly power P = 0.472 Q (MW) Q = lower value of C.I.*
100-149	3	120	100	47.2
150-199	4	117	97.5	70.8
200-249	16	113	94.2	94.4
250-299	21	97	80.8	118
300-349	24	76	63.3	142
350-399	21	52	43.3	165
400-499	20	⟶ 31	25.8	189
450-499	9	+ ⟶ 11	9.2	212
500-549	2	+ ⟶ 2	1.7	236
	Total n = 120			

Note: For drought–duration studies, m = No. of times equal to or less than the flow value and has to be worked from the top; percent of time ≤ the flow value is $\frac{m}{n} \times 100$. In this example, m = 3, 7, 23, 44, ... and % of time ≤ Q are 2.5, 5.83, 19.2, 36.7. ...., respectively (from top).

continuous flow that can be expected almost throughout the year (*i.e.,* for a major percent of time) is required particularly in drought duration and power duration studies, while in flood flow analysis the CI may be arranged in the descending order of magnitude and m is worked out from the top as cumulative number of occurrences since the high flows are of interest. The percent of time that each CI is equalled or exceeded is worked out as the percent of the total number of occurrences (m) of the particular CI out of the 120 (= 10 yr × 12 = n) mean monthly flow values, *i.e.,* $= \frac{m}{n} \times 100$. The monthly power developed in megawatts,

$$P = \frac{gQH}{1000} \times \eta_0 = \left(\frac{9.81 \times 60}{1000} \times 0.80\right) Q$$

$$P = 0.472\ Q$$

where Q is the lower value of the CI Thus, for each value of Q, P can be calculated.

(*i*) The flow duration curve is obtained by plotting Q vs. percent of time, Fig. 10.5, (Q = lower value of the CI).

(*ii*) The power duration curve is obtained by plotting P vs. percent of time, Fig. 10.5.

(*b*) The mean monthly flow that can be expected is the flow that is available for 50% of the time *i.e.,* 357.5 cumec from the flow duration curve drawn. The average power that can be developed *i.e.,* from the flow available for 50% of the time, is 167 MW, from the power duration curve drawn.

(*c*) The effect of storage is to raise the flow duration curve on the dry weather portion and lower it on the high flow portion and thus tends to equalise the flow at different times of the year, as indicated in Fig. 10.5.

(*d*) If the mean weekly flow data are used instead of the monthly flow data, the flow duration curve lies below the curve obtained from monthly flows for about 75% of the time towards the drier part of the year and above it for the rest of the year as indicated in Fig. 10.5.

In fact the flow duration curve obtained from daily flow data gives the details more accurately (particularly near the ends) than the curves obtained from weekly or monthly flow data but the latter provide smooth curves because of their averaged out values. What duration is to be used depends upon the purpose for which the flow duration curve is intended.

10.3 PONDAGE

While storage refers to large reservoirs to take care of monthly or seasonal fluctuations in the river flow, pondage usually refers to the small storage at the back of a weir, in run-of-river plants, for temporarily storing water during non-working hours, idle days and low load periods for use during hours of peak load demand. Run-of-river plants are feasible for streams which have a minimum dry weather flow or receive flow as regulated by any storage reservoir upstream.

Pondage factor is the ratio of the total inflow hours in a week to the total number of hours of working of the power plant in that week. For example, assuming constant stream flow, if a power plant operates for 6 days in a week at 8 hours per day, then the pondage factor would be $\frac{7 \times 24}{6 \times 8}$ = 3.5, and if the plant works only for 5 days in a week, the pondage factor would be $\frac{7 \times 24}{5 \times 8}$ = 4.2 and the pondage required in the latter case would be $\frac{48+16}{24}$ × daily flow volume = $\frac{8}{3}$ of daily flow-volume.Thus the pondage factor serves as a rough guide of the amount of pondage required when the stream flow is constant and the plant works only for a part of the period. Pondage is needed to cover the following four aspects:

(*i*) To store the idle day flow.

(*ii*) For use during hours of peak load.

(*iii*) To balance the fluctuations in the stream flow.

(*iv*) To compensate for wastage (due to leakage) and spillage.

Example 10.3 *The available flow for 97% of the time (i.e., in a year) in a river is 30 cumec. A run-of-river plant is proposed on this river to operate for 6 days in a week round the clock. The plant supplies power to a variable load whose variation is given below:*

Period (hr)	*0–6*	*6–12*	*12–18*	*18–24*
$\frac{\textit{Load during period}}{\textit{24-hr average load}}$ *ratio*	*0.6*	*1.4*	*1.5*	*0.5*

The other relevant data are given below:

Head at full pond level	*= 16 m*
Maximum allowable fluctuation of pond level	*= 1 m*
Plant efficiency	*= 80%*
Pondage to cover inflow fluctuations	*= 20% of average daily flow*
Pondage to cover wastage and spillage	*= 10%*

Determine:

(i) the average load that can be developed

(ii) daily load factor

(iii) plant capacity

(iv) weekly energy output

(v) pondage required and the surface area of the pond for satisfactory operation

Solution (*i*) 7 days flow has to be used in 6 days

∴ Average flow available for power development

$$Q = 30 \times \tfrac{7}{6} = 35 \text{ cumec}$$

Since maximum allowable fluctuation of pond level is 1 m, average head

$$H = \frac{16+15}{2} = 15.5 \text{ m}$$

The average load that can be developed

$$P = \frac{gQH}{1000} \times \eta_0$$

$$= \frac{9.81 \times 35 \times 15.5}{1000} \times 0.8 = \mathbf{4.27\ MW}$$

(ii) Daily load factor = $\dfrac{\text{average load}}{\text{peak load}} = \dfrac{1}{1.5}$ = **0.67**

(iii) Plant capacity = 4.27 × 1.5 = **6.4 MW**

(iv) Weekly energy output = Average load in kW × No. of working hours

= (4.27 × 1000)(6 × 24) = **6.15×10^5 kWh**

It should be noted that the installed capacity has to be equal to the peak load and the number of units (kWh) generated will be governed by the average load.

(v) Pondage required

(a) to store the idle day's flow = 30 × 86400 = 2.592×10^6 m^3, or 2.592 Mm^3

(b) to store the excess flow during low loads to meet the peak load demand. Since power developed is proportional to discharge (assuming constant average head of 15.5 m), flow required during peak load periods of 6.00 to 12.00 hr is (1.4 – 1) 35 cumec and from 12.00 to 18.00 hr is (1.5 – 1) 35 cumec.

∴ pondage to meet peak load demand

= (0.4 + 0.5) 35 cumec for 6 hr

= (0.9 × 35)(6 × 60 × 60)

= 6.81×10^5 m^3, or 0.681 Mm^3

(c) pondage to cover inflow fluctuations

= (0.20 × 30) 86400

= 5.18×10^5 m^3, or 0.518 Mm^3

Total of (a), (b) and (c) = 3.791 Mm^3

Add 10% for wastage and spillage = **0.379 Mm^3**

Total pondage required = 4.170 Mm^3

Since the maximum fluctuation of pond level is 1 m

the surface area of pond = 4.170×10^6 m^2

or 4.17 km^2, or **417 ha**

Example 10.4 *A run-of-river hydroelectric plant with an effective head of 22 m and plant efficiency of 80% supplies power to a variable load as given below:*

	Time (hr)	*Load (1000 kW)*	*Time (hr)*	*Load (1000 kW)*
MN	0-2	11.4	12-14	44.2
	2-4	5.6	14-16	44.4
	4-6	25.6	16-18	74.2
	6-8	53.2	18-20	37.8
	8-10	44.8	20-22	30.0
N	10-12	39.4	22-24	18.0

Draw the load curve and determine:

(i) *the minimum average daily flow to supply the indicated load.*

(ii) *pondage required to produce the necessary power at the peak.*

(iii) *the plant load factor.*

Solution (*i*) The load curve is shown in Fig. 10.6.

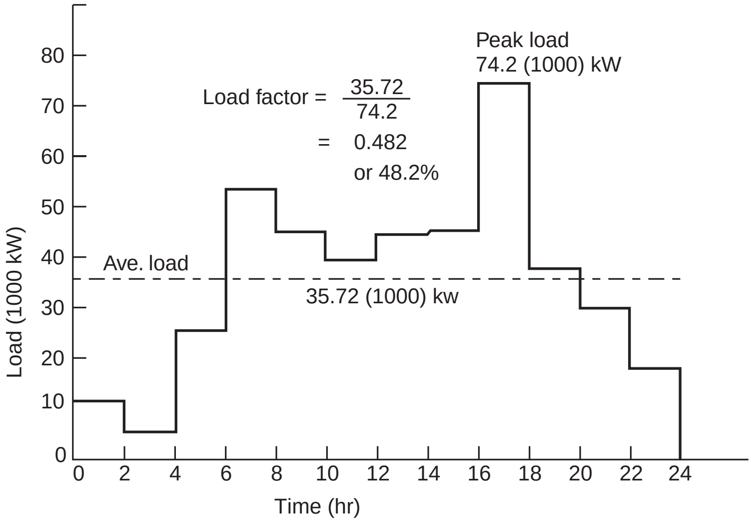

Fig. 10.6 Daily load curve (Example 10.4)

Total of loads at 2 hr intervals = 428.6 kW

Average load = $\dfrac{428.6 \times 1000 \text{ kW} \times 2\text{hr}}{24 \text{ hr}}$ = 35.72 × 1000 kW

Flow (Q) required to develop the average load

$$\frac{1000 \times 9.81 \times Q \times 22}{1000} \times 0.8 = 35.72 \times 1000$$

∴ Q = **207 cumec**

(*ii*) Flow required to produce the required load demand

$$Q = \frac{207}{35.72} \times \text{Load in 1000 kW}$$

∴ Q = 5.8 × Load in 1000 kW

To determine the pondage capacity the following table is prepared:

	Time (hr)	*Load (1000 kW) P*	*Required flow (cumec) 5.8 P*	*Deviation from the average flow of 207 cumec*	
				Deficiency (cumec)	*Excess (cumec)*
MN:	0-2	11.4	66.10		140.90
	2-4	5.6	32.46		174.54
	4-6	25.6	148.40		58.60
	6-8	53.2	308.20	101.20	
	8-10	44.8	260.00	53.00	
N:	10-12	39.4	228.50	21.50	
	12-14	44.2	256.00	49.00	
	14-16	44.4	257.40	50.40	

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16-18	74.2	430.00	223.00	
18-20	37.8	219.40	12.40	
20-22	30.0	174.00		33.00
22-24	18.0	104.30		102.70
Total:	428.6		510.50	509.74

From the above table

$$\text{Total deficiency} = \text{total excess} = 510 \text{ cumec}$$

$\therefore$ Pondage capacity required = 510 cumec for 2 hr

$$= 510\,(2 \times 60 \times 60) = \mathbf{3.67\ Mm^3}$$

(*iii*) Plant Load factor $= \dfrac{\text{average load}}{\text{peak load}}$

$$\text{L.F.} = \frac{35.72}{74.20} = 0.482 \quad \text{or} \quad \mathbf{48.2\%}.$$

QUIZ X

I Choose the correct statement/s in the following:

1 From a reservoir mass curve the following information may be obtained:
- (*i*) the storage capacity required for a uniform discharge and power output.
- (*ii*) the maximum discharge possible and power output for a specified storage capacity.
- (*iii*) the month when the reservoir is empty or just fall.
- (*iv*) the months during which water is overflowing over the spillway.
- (*v*) the reservoir pool elevation at any time.
- (*vi*) all the above.

2 A flow duration curve indicates
- (*i*) the stream flow available for different percent of time
- (*ii*) the firm power
- (*iii*) the duration of floods or droughts
- (*iv*) the effect of storage
- (*v*) the power available for different percent of time
- (*vi*) all the above times.

3 Pondage is required across a river
- (*i*) which becomes dry in summer
- (*ii*) which gets occasional releases from an upstream reservoir
- (*iii*) which has a sustained dry weather flow
- (*iv*) to take care of seasonal fluctuations of streamflow
- (*v*) to store water during off-hours, idle day and low load periods, for use during hours of peak load
- (*vi*) to compensate for the losses due to evaporation, leakage and spillage
- (*vii*) for all the above cases.

(1. *vi*; 2. *vi*; 3. *iii, iv, v, vi*)

II Match the items in 'A' with items in 'B'

A	B
(*i*) Storage	(*a*) 97% of time on power-duration curve
(*ii*) Pondage	(*b*) Arid region
(*iii*) Minimum hydrorate	(*c*) Run-of-river plant
(*iv*) Drought-duration	(*d*) Reservoir mass curve

III Say 'true' or 'false'; if false, give the correct statement:

(*i*) A mass curve is a graphical representation of cumulative inflow into the reservoir versus time.

(*ii*) The vertical distance between the successive tangents to the mass curve peaks (the slopes of the tangents = demand rates) represents the storage capacity of the reservoir.

(*iii*) The slope of the mass curve at any point gives the inflow rate at that time into the reservoir.

(*iv*) The draw-off rates are marked by drawing tangents at the peaks, having slopes equal to the demand rates.

(*v*) The maximum departure between the demand line and the mass curve gives the water wasted over the spillway.

(*vi*) A demand line must intersect the mass curve when extended forward, otherwise the reservoir is not going to refill.

(*vii*) The maximum departure of the mass curve of water use and mass curve of inflow indicates the month of maximum draft in the reservoir.

(*viii*) The weekly flow duration curve lies above that of the monthly flow for about 75% of the time (towards the drier part of the year) and below it for the rest of the year.

(*ix*) Though the daily flow duration curve gives the details more accurately (particularly near the ends), the weekly or monthly flow duration curves plot smooth curves (because of their averaged out values).

(*x*) Larger the period of record, more accurate and flatter is the flow duration curve.

(*xi*) The effect of storage is to lower the flow duration curve on the dry weather portion and raise it on the high flow portion, thus depicting marked variation in the flow at different times of the year.

(*xii*) The pondage factor for a constant river discharge into a pond with 8-hour plant operation per day for 6 days in a weak is 3.5, neglecting Sunday (idle-day) and the pondage required is 5/3 of the daily-flow volume.

(*xiii*) Run-of-river plants are feasible for streams, which do not have a sustained dry weather flow or receive flow releases occasionally as regulated by an upstream reservoir.

(*xiv*) The flow-duration curves are useful for drought-duration studies particularly in semi-arid regions. (false: *ii, v, vii, x, xi, xii*)

QUESTIONS

1 (*a*) Sketch a mass curve of run-off and explain how it is helpful in determining:

(*a*) the storage required to satisfy a given constant demand.

(*b*) the safe yield available from a given storage.

(*b*) The estimated monthly flow in a river is as follows:

Month	*Flow* (*Mm*^{3})	*Month*	*Flow* (*Mm*^{3})
Jan.	7.6	July	10.7
Feb.	19.5	Aug.	13.0
March	17.3	Sept.	19.2
April	10.5	Oct.	17.2
May	5.9	Nov.	10.5
June	6.8	Dec.	6.8

The available fall is 42 m. What size of reservoir will be necessary to give the greatest continuous uniform output and what will be this power if the plant efficiency is 70%. If the largest reservoir, which can be economically constructed has a capacity of 8.8 Mm^3, what will be then the greatest output?

2 (*a*) Give the method of finding out the size of reservoir using stream flow records and demand.

(*b*) The following is a record of mean monthly discharges of a river in a dry year:

Month	*Mean flow (cumec)*	*Month*	*Mean flow (cumec)*
April	56.6	Oct.	161.5
May	62.2	Nov.	133.0
June	119.0	Dec.	190.0
July	258.0	Jan.	212.3
Aug.	234.0	Feb.	184.0
Sept.	201.5	March	127.5

The average net head available is 30.5 m and the average efficiency of a hydro-electric plant may be taken as 85%. Estimate the storage required to produce a firm power of 40 MW and the maximum firm power available.

3 The monthly inflow into a reservoir is as follows:

Month	*Flow (Mm^3)*	*Month*	*Flow (Mm^3)*
Jan.	340	July	400
Feb.	360	Aug.	300
March	300	Sept.	310
April	270	Oct.	330
May	240	Nov.	350
June	290	Dec.	320

The water turbines have an output of 22.5 MW working under a net head of 24 m and overall efficiency of 80%.

Determine the minimum capacity of the reservoir to satisfy the uniform demand for water and the total quantity of water wasted during the year assuming that at the beginning of January, the reservoir is full.

4 The quantity of water flowing in a river during each successive month is given below in Mm^3.

4.2, 5.1, 8.5, 27.5, 45.3, 30.6, 14.2, 11.1, 10.2, 9.3, 8.8.

Determine the minimum capacity of a reservoir, if the above water is to be drawn off at a uniform rate and there should be no loss by flow over the spillway.

Also estimate the amount of water, which must be initially stored to maintain the uniform draw off.

Also calculate the electrical energy that could be generated per year, if the average available head is 36.5 m and the plant efficiency is 80%.

5 The following is a record of the power demand and of the streamflow taken in a day, for every 2-hr intervals (the record gives the average for the two hour periods).

	Time (hr)	Power demand (1000 kW)	Stream flow (cumec)
MN:	0-2	11.4	59.5
	2-4	5.6	57.4
	4-6	25.6	55.2
	6-8	53.2	53.8
	8-10	44.8	52.4
N:	10-12	39.4	51.0
	12-14	44.2	49.6
	14-16	44.4	51.0
	16-18	74.2	52.4
	18-20	37.8	53.8
	20-22	30.0	55.2
	22-24	18.0	56.6

The average net head available is 109.3 m. The average plant efficiency is 85%. Determine the necessary storage, if the demand is to be just met.

6 Explain the significance of the terms; flow-duration curves, mass curves, pondage and storage. State the limiting conditions for economic storage and utilization of water resources in a country where the majority of rivers are not perennial?

Sketch one in which the power potential can be augmented further downstream.

7 Construct a mass curve from the following data of flow for a given site.

Weeks	*Weekly flow (cumec)*
1-6	600
7-12	700
13-18	300
19-24	400
25-30	1700
31-36	1300
37-42	900
43-48	600
49-52	300

Estimate the size of reservoir and the possible maximum rate of flow that could be available from it. (5500 Mm^3, 773 cumec)

8 The average weekly discharge as measured at a given site is as follows:

Week	*Flow (cumec)*	*Week*	*Flow (cumec)*
1	1000	14	1200
2	900	15	1000
3	909	16	900
4	800	17	800
5	800	18	500
6	600	19	400
7	500	20	400
8	500	21	300
9	800	22	300
10	800	23	400
11	1000	24	400
12	1100	25	500
13	1100	26	500

Plot

(*a*) the hydrograph of weekly flow.

(*b*) the flow-duration curve.

(*c*) the power-duration curve if the head available is 50 m and the efficiency of the turbine-generator set is 85%.

Determine the power that can be developed per cumec, the maximum power, average power, and total energy produced during 26 weeks. (417 kW, 485 MW, 300 MW, 1.31 GWh)

9 Average daily flows in a river in typical low water week are given below. A run-of-river plant is proposed on this river to operate for 6 days in a week round the clock. The full pond effective head on turbines is 20 m and the plant efficiency is 80%. Maximum allowable fluctuation of pond level is 1 m.

Determine

(*i*) the capacity of the pond required to give a maximum uniform output.

(*ii*) the surface area of pond for satisfactory operation.

(*iii*) the weekly energy output (KWH) from the plant.

Day:	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
Flow (cumec):	26	35	40	50	45	40	30

10 Typical weekly and daily releases of water from an upstream reservoir on a river are given below. Estimate the pondage capacity to operate a run-of-river plant at downstream location so that a steady uniform power output is available from the plant.

Weekly release pattern

Day:	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
Flow: release (cumec)	25	30	40	50	40	35	25

Daily release pattern

Time (hr):	0-6	6-12	12-18	18-24
% of ave. daily flow volume:	5	35	50	10

(**Hint** Pondage reqd. = weekly fluctuations + daily fluctuations)

11 During a low water week, the average daily flow in a river is 30 cumec and the pondage required for the daily fluctuation is about 20% of the average daily flow. A run-of-river plant to be located on the river is to operate 6 days a week, round the clock and is connected to a variable load with a daily load factor of 50%. The pondage required for the daily load fluctuation may be taken as about one-fifth of the mean flow to the turbine.

If the effective head on the turbine when the pond is full is 20 m and the maximum allowable fluctuation in pond level is 1 m, determine

(*i*) the capacity of the pond and its surface area.

(*ii*) the weekly energy output (KWH).

Assume a plant efficiency of 80%.

Reservoir Sedimentation Process

As sediment enters a reservoir it deposits as the flow velocity reduces. The coarser portion of the sediment load deposits in a delta at the upstream end of the reservoir and the finer portion deposits in reaches closer to the dam (Figure 1). The sediment profile can be described by: the **topset,** the **foreset** and the **bottom set.**

- The topset is the gently inclining portion of the delta at the upstream end of the reservoir.
- The foreset is the steep slope at the front of the delta.
- The bottom set is the flat portion in front of the delta.

The intersection of the topset and foreset is termed the pivot point. As more sediment enters the reservoir, the bottom set gradually increases in thickness and the foreset moves forwards.

Reservoir Sedimentation

Reservoir Sedimentation Process

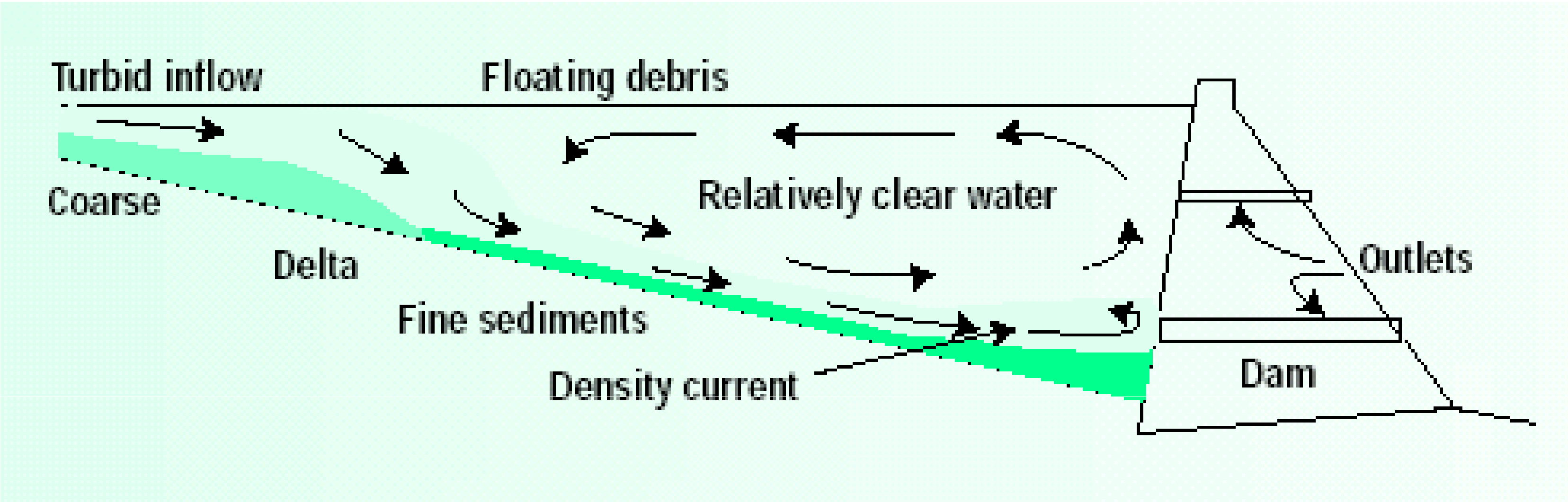


Figure 1: Sedimentation process (Pamieri, et al. 2003)

Reservoir Sedimentation Process

In some instances sediments can flow into a reservoir as a **density current.**

This phenomenon can occur when the sediment concentration in the inflowing river is much higher than the water in the impoundment and/or there is a significant temperature difference between the incoming flow and the impounded water.

Under such circumstances the density current may flow under the impounded water in the reservoir toward the dam. If the density current is not allowed to flow through the dam by means of low-level gates, a technique known as density current venting, it will curl up at the dam and its return-flow will mix with the clearer water in the reservoir. The sediment thus mixed into the clearer water will deposit with time

Reservoir Sedimentation Process

Most dams have been designed with a dead storage capacity below which there are no outlets and therefore the water in this zone cannot be used.

Many designers incorrectly assumed that sediments would naturally deposit in this dead storage. As described above, this is not the case and a good proportion of the sediments deposited are found in the upper reaches of the reservoir, thus reducing the live storage volume.

Sedimentation has a number of consequences: depletion of storage (reducing yield and flood attenuation capability), abortion of outlet structures, (e.g., spillways) and mechanical equipment (e.g., turbines)

Reservoir sediment distribution was estimated based on the Empirical-Area-reduction method (USBR, 1987), which is explained as follows. Based on the sediment resurvey data of several reservoirs in USA, Borland and Mille (1960) identified four standard types of reservoirs (Table 1).

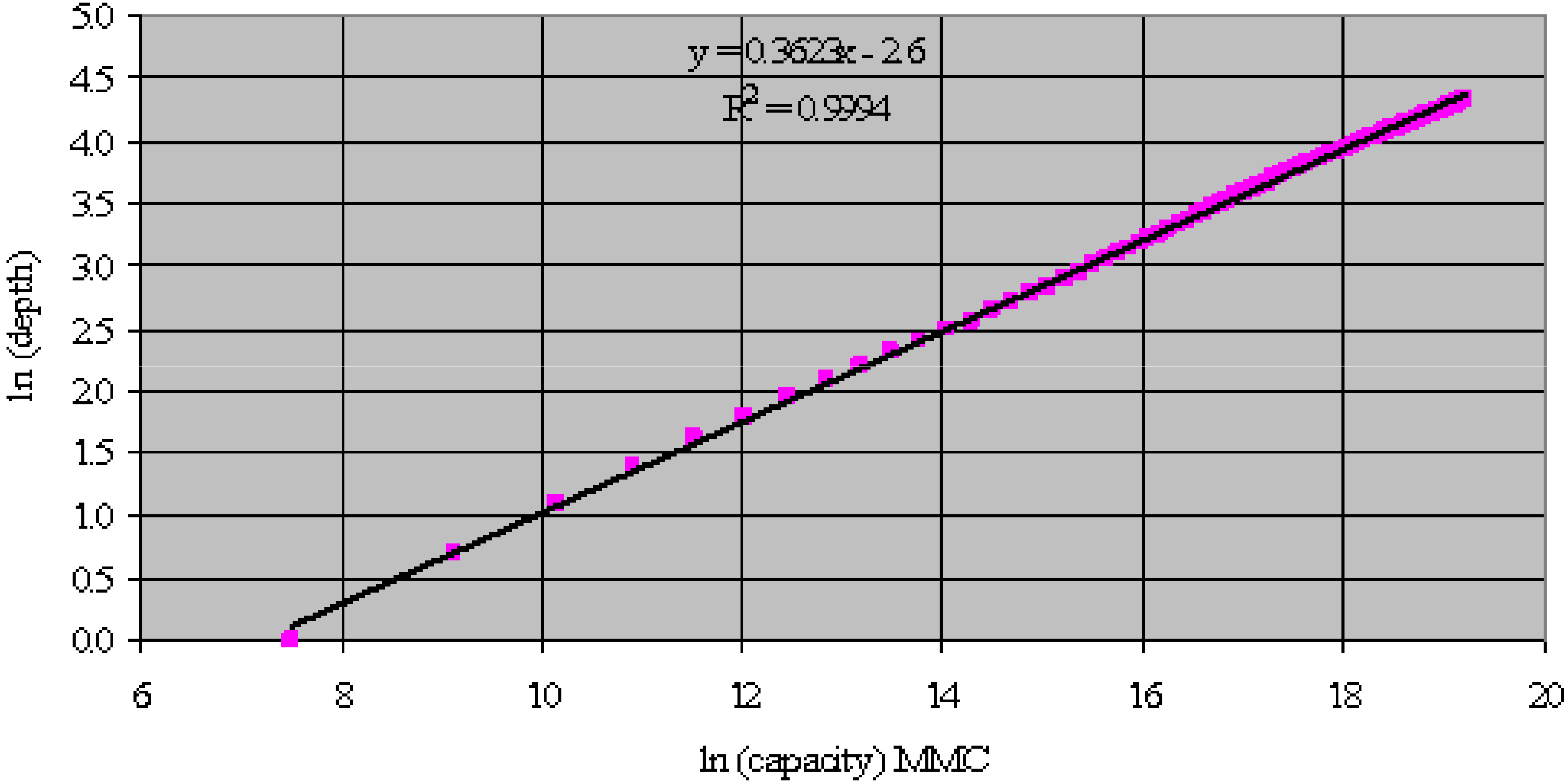
m = the reciprocal of the slope of the line obtained by plotting the reservoir depth as ordinate and reservoir capacity as the abscissa on log-log paper (Figure 2)	Reservoir type	Standard classification
1 – 1.5	Gorge	IV
1.5 – 2.5	Hill	III
2.5 – 3.5	Flood plain, foothill	II
3.5 – 4.5		I

They also gave four types of relationships between the reservoir shape and percentage of sediment deposition at various depths throughout the reservoir.

The shape of the reservoir is defined by the depth capacity relationship called m = 1/ slope of the line as shown in Figure 2.

For the Example Reservoir m is 2.76 and thus it is classified as Flood plain, foothill reservoir type (lower end of Type II reservoir). The reservoir is expected to have a considerable drawdown – that is at the beginning of the rainy season the reservoir is nearly empty – in this case according to the USBR (1987) it is classified as type III, and the weighted reservoir type is thus Type III.

Reservoir Sedimentation Distribution



Reservoir Sedimentation Distribution

The amount of sediment deposited within a reservoir depends on the trap efficiency.

Reservoir trap efficiency is the ratio of the deposited sediment to the total sediment inflow and depends primarily upon the fall velocity of the various sediment particles, flow rate and velocity through the reservoir (Strand and Pemberton, 1982), as well as the size, depth, shape, and operation rules of the reservoir. The particle fall velocity is a function of particle size, shape, and density; water viscosity; and the chemical composition of the water and sediment. The rate of flow through the reservoir can be computed as the ratio of reservoir storage capacity to the rate of flow.

Reservoir Sedimentation

Reservoir Sedimentation Distribution

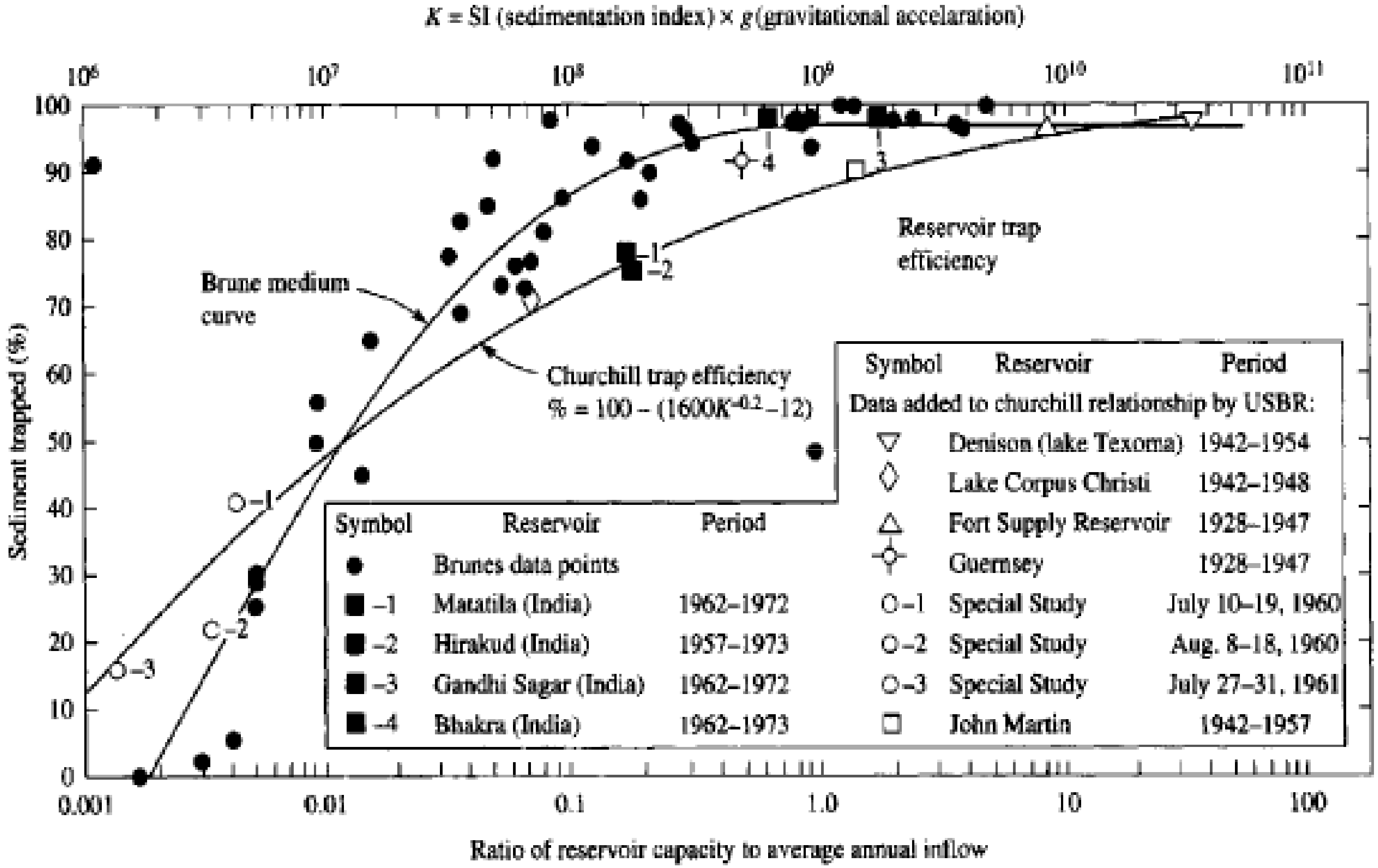


Figure 2.19. Trap efficiency curves (Churchill, 1948; Brune, 1953).

Reservoir Sedimentation

Reservoir Sedimentation Distribution

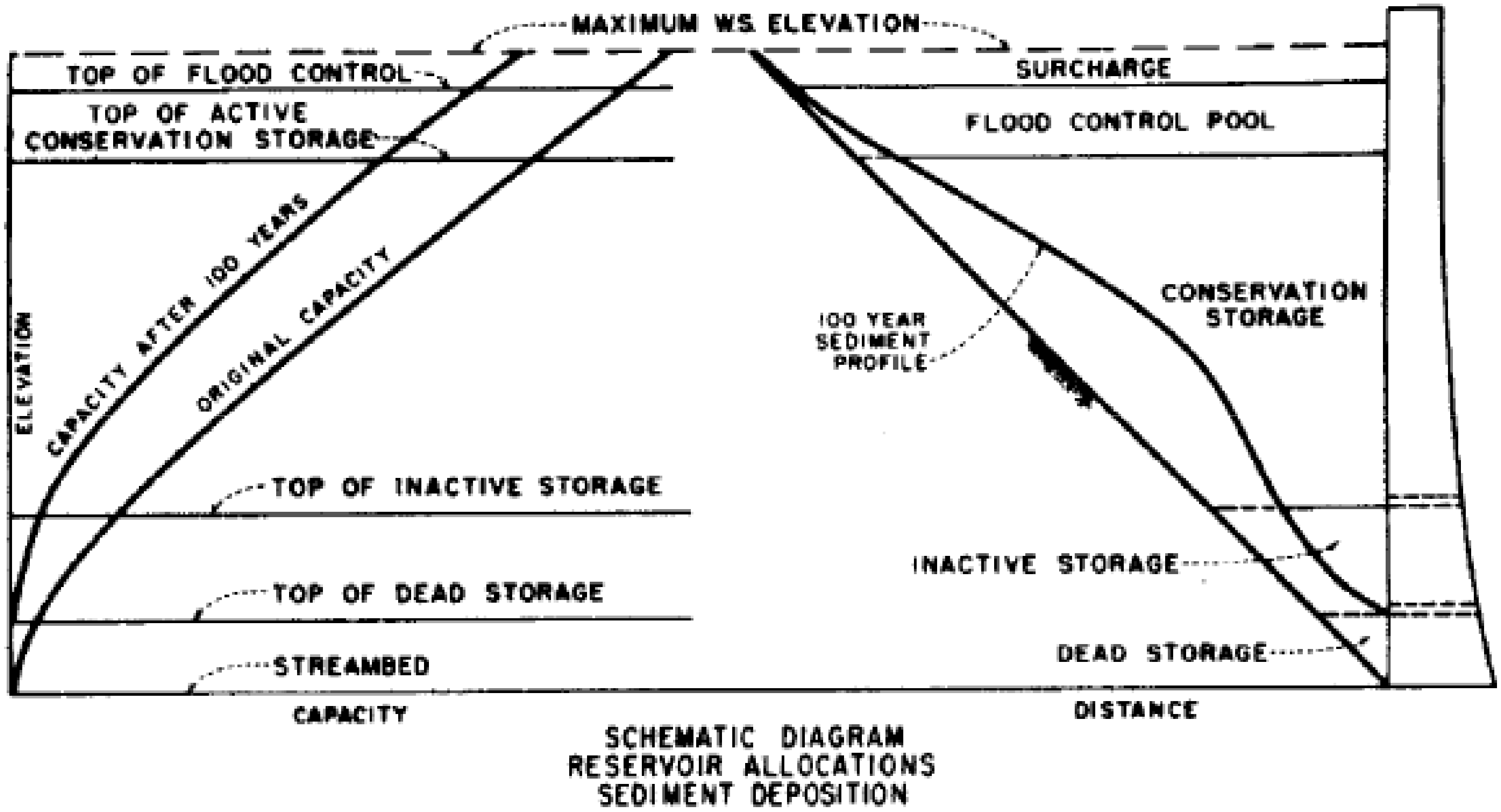


Figure 2.20. Schematic diagram of anticipated sediment deposition (Bureau of Reclamation, 1987).

Reservoir Sedimentation

Reservoir Sedimentation Distribution

A general guideline is to use the Brune method for large storage or normal ponded reservoirs and the Churchill curve for settling basins, small reservoirs, flood retarding structures, semi-dry reservoirs, or reservoirs that are continuously sluiced.

When the anticipated sediment accumulation is larger than 10 percent of the reservoir capacity, it is necessary that the trap efficiency be analyzed for incremental periods of the reservoir life.

Density of sediment:

Basic factors influencing density of sediment deposits in a reservoir are:

(I) the manner in which the reservoir is operated;
(II) the size of deposited sediment particles; and
(III the compaction or consolidation rate of deposited sediments

Reservoir Sedimentation Distribution

Three factors that should be taken into account in determining the density of deposited sediment are presented below.

The influence of **reservoir operation** is the most significant because of the amount of consolidation or drying out that can occur in the clay fraction of the deposited material when a reservoir is subjected to considerable drawdown.
The **size of sediment particles** entering the reservoir will also affect density, as shown by the variation in initial masses. Lara and Pemberton (1965) statistically analyzed some 1,300 samples for determining mathematical equations of variation of the unit weight of the deposits with the type of reservoir operation.

Additional data on unit weight of deposited material from reservoir resurveys have supported the Lara and Pemberton (1965) equations (see Equation 2.39). The third factor is the years of operation of the reservoir.

Reservoir Sedimentation

Reservoir Sedimentation Distribution

The size of the incoming sediment particles has a significant effect upon density. Sediment deposits composed of silt and sand will have higher densities than those in which clay predominates. The classification of sediment according to size as proposed by the American Geophysical Union (Vanoni, 1975) is as follows:

Sediment type	Size range in millimeters
Clay	Less than 0.004
Silt	0.004 to 0.062
Sand	0.062 to 2.0

Reservoir operations were classified according to operation as follows:

Operation	Reservoir operation
1	Sediment always submerged or nearly submerged
2	Normally moderate to considerable reservoir drawdown
3	Reservoir normally empty
4	Riverbed sediments upstream of reservoir

Selection of the proper reservoir operation number usually can be made from the operation study prepared for the reservoir.

Reservoir Sedimentation

Reservoir Sedimentation Distribution

$$W = W_c p_c + W_m p_m + W_s p_s \tag{2.39}$$

where W = unit weight (lb/ft^3 or μg/m^3),
p_c, p_m, p_s = percentages of clay, silt, and sand, respectively, of the incoming sediment, and
W_c, W_m, W_s = unit weight of clay, silt, and sand, respectively, which can be obtained from the following tabulation:

Operation	Initial unit weight in lb/ft^3 (kg/m^3)		
	W_c	W_m	W_s
1	26 (416)	70 (1,20)	97 (1,50)
2	35 (561)	71 (1,40)	97 (1,50)
3	40 (641)	72 (1,50)	97 (1,50)
4	60 (961)	73 (1,70)	97 (1,50)

Reservoir Sedimentation

Reservoir Sedimentation Distribution

In determining the density of sediment deposits in reservoirs after a period of reservoir operation, it is recognized that part of the sediment will deposit in the reservoir in each of the T years of operation, and each year's deposits will have a different compaction time. Miller (1953) developed an approximation of the integral for determining the average density of all sediment deposited in T years of operation as follows:

$$W_T = W_o + 0.4343K \frac{T}{T-1}\left(\log_e T\right) - 1 \qquad (2.40)$$

where W_T = average density after T years of reservoir operation,
W_o = initial unit weight (density) as derived from Equation (2.39), and
K = constant based on type of reservoir operation and sediment size analysis as obtained from the following table:

Reservoir operation	K for English units (metric units)		
	Sand	Silt	Clay
1	0	5.7	16
2	0	1.8	8.4
3	0	0	0

Reservoir Sedimentation

Reservoir Sedimentation Distribution

The K-factor of Equation (2.40) can be computed using Equation (2.41).

$$K = K_c p_c + K_m p_m + K_s p_s \tag{2.41}$$

where K_c, K_m, and K_s = the unit weight of clay, silt, and sand, respectively

As an example, the following data are known for a proposed reservoir with an operation number of 1 and a sized distribution of 23 percent clay, 40 percent silt, and 37 percent sand.

Then:

$$W = 26\ (0.23) + 70\ (0.40) + 97\ (0.37) = 6.0 + 28.0 + 35.9 = 70\ \text{lb/ft}^3\ (1120\ \text{kg/m}^3)$$

The 100-year average values to include compaction are computed as follows:

$$K = 16\ (0.23) + 5.7\ (0.40) + 0\ (0.37) = 3.68 + 2.28 + 0 = 5.96$$

$$W_{100} = 70 + 0.04343\,(5.96)\left[\frac{100}{99}(4.61) - 1\right] = 70 + 2.59\,(3.66) = 79\ \ \text{lb/ft}^3$$

This value may then be used to convert the initial weights (initial masses) of incoming sediment to the volume it will occupy in the reservoir after 100 years.

Reservoir Sedimentation

Reservoir Sedimentation Distribution

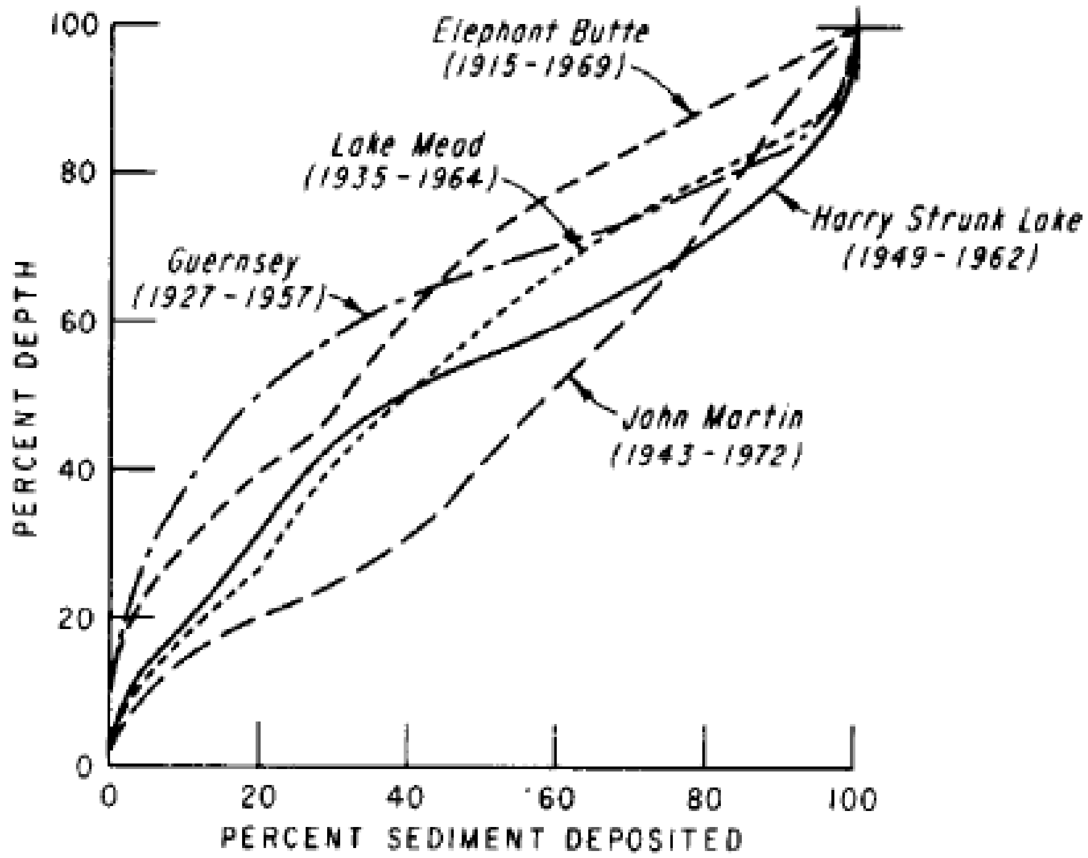


Figure 2.23. Sediment deposition profiles of several reservoirs (Bureau of Reclamation, 1987).

Reservoir Sedimentation

Reservoir Sedimentation Distribution

The design curve shown in Figure 2.25 can be used to predict reservoir sediment distribution as a function of depth. With equal weight applied to reservoir operation and shape, a weighted type distribution is selected from Table 2.34. In those cases where a choice of two weighted types are given, then a judicious decision can be made on whether the reservoir operation or shape of reservoir is more influential. The predominant size of reservoir sediment could be considered in this judgment of reservoir type from the following guidelines (see Figure 2.25):

Predominant size	Type
Sand or coarser	I
Silt	II
Clay	III

Table 2.34.   Design type curve selection

Reservoir operation		Shape		
Class	Type	Class	Type	Weighted type
Sediment submerged	I	Lake	I	I
		Flood plain - foothill	II	I or II
		Hill and gorge	III	II
Moderate drawdown	II	Lake	I	I or II
		Flood plain - foothill	II	II
		Hill and gorge	III	II or III
Considerable drawdown	III	Lake	I	II
		Flood plain - foothill	II	II or III
		Hill and gorge	III	III
Normally empty	IV	All shapes		IV

Reservoir Sedimentation

Reservoir Sedimentation Distribution

Empirical-Area-Reduction methods:

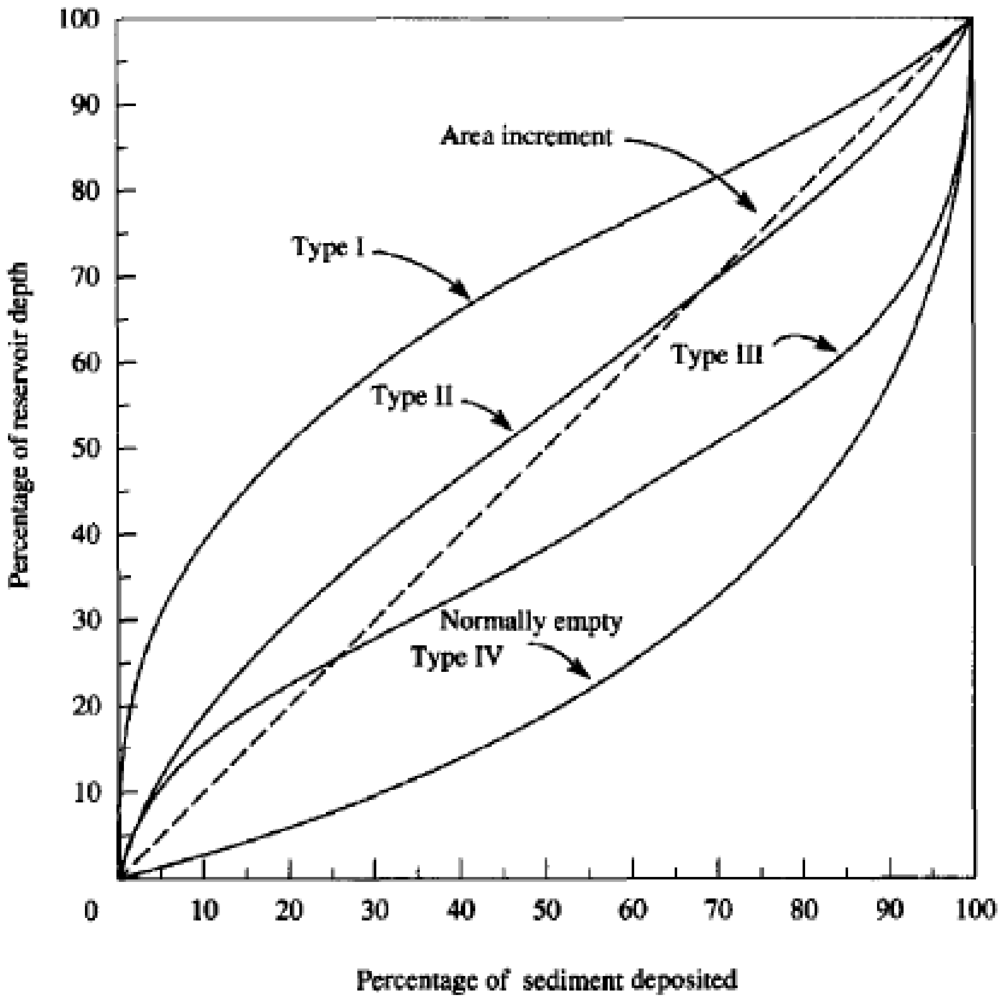


Figure 2.25. Sediment distribution design curves (Bureau of Reclamation, 1987).

Reservoir Sedimentation

Reservoir Sedimentation Distribution

Empirical-Area-Reduction methods:

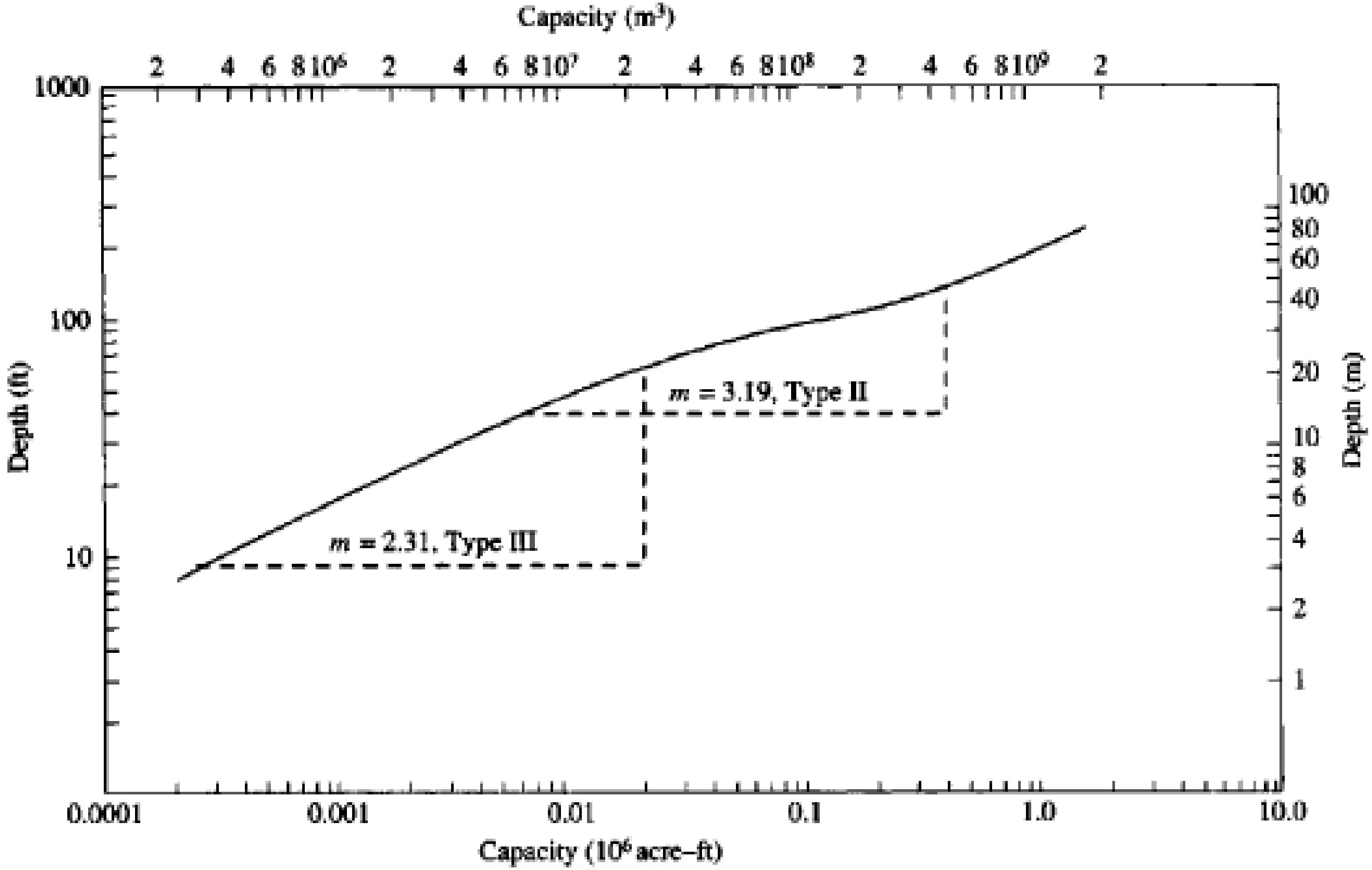


Figure 2.27. Depth versus capacity for Theodore Roosevelt Lake (Bureau of Reclamation, 1987).

Reservoir Sedimentation

Reservoir Sedimentation Distribution

Empirical-Area-Reduction methods:

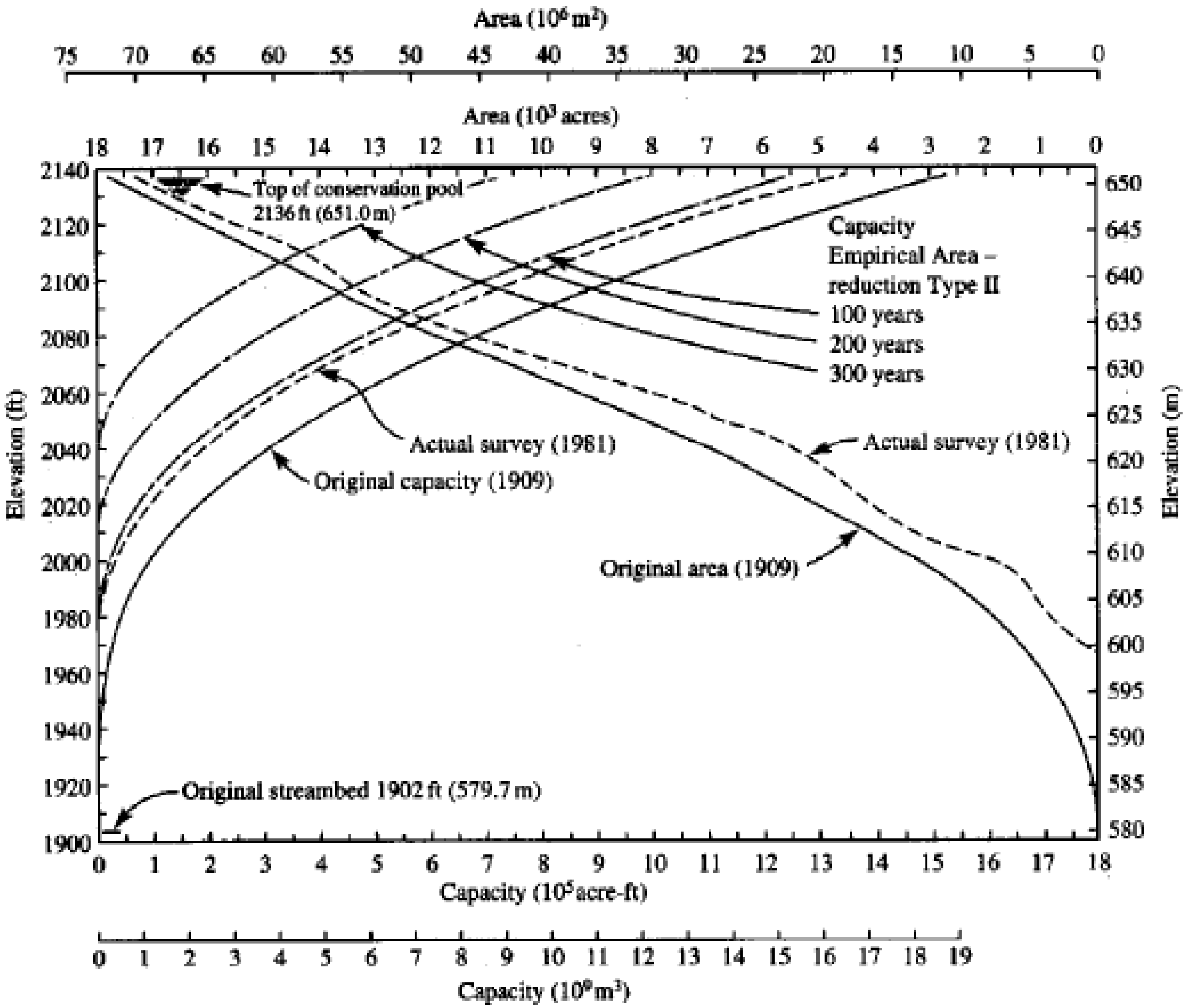


Figure 2.26. Area and capacity curves for Theodore Roosevelt Lake (Bureau of Reclamation, 1987).

Empirical-Area-Reduction methods:

Type	*Equation*	
I	$a = 5.074\ p^{1.85}(1-p)^{0.35}$	(6)
II	$a = 2.487\ p^{0.57}(1-p)^{0.41}$	(7)
III	$a = 16.967\ p^{1.15}(1-p)^{2.32}$	(8)
IV	$a = 1.486\ p^{-0.25}(1-p)^{1.34}$	(9)

where:

a = relative sediment area, and

p = relative depth of reservoir measured from the bottom.

Empirical-Area-Reduction methods:

No.	water surface elevation	Original area	Original Capcity (NWL = 1947.1 m)	Depth	Relative depth	Ap Type III	Sediment area	Sediment volume	Accumulated sediment	Modified Accumulated	Reservoir area after 50 years (ha)	Reservoir Capacity after 50 years
					p		K Ap	((A1+A2)/2)*H /100	volume	volume	[3]-[8]	(Mm3)
	(m)	(ha)	(Mm3)	(m)	[5]/Max depth		(ha)	(Mm3)	(Mm3)	(Mm3)	ha	[4]-[11]
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
1	1947.1	803.886	181.908	71.1	1.000	0.000	0.0	0.000	20.71	20.7	803.9	161.20
2	1947	801.346	181.094	71	0.999	0.000	0.0	0.000	20.7	20.7	801.3	160.38
3	1946	776.371	173.205	70	0.985	0.001	0.0	0.001	20.7	20.7	776.3	152.50
4	1945	751.824	165.564	69	0.970	0.005	0.1	0.003	20.7	20.7	751.7	144.86
5	1944	727.705	158.166	68	0.956	0.011	0.4	0.005	20.7	20.7	727.3	137.46
6	1943	704.014	151.008	67	0.942	0.021	0.7	0.009	20.7	20.7	703.3	130.31
7	1942	680.750	144.084	66	0.928	0.034	1.1	0.014	20.7	20.7	679.6	123.39
8	1941	657.914	137.391	65	0.914	0.051	1.6	0.020	20.7	20.7	656.3	116.71
9	1940	635.506	130.923	64	0.900	0.072	2.3	0.027	20.7	20.7	633.2	110.26
10	1939	613.526	124.678	63	0.886	0.096	3.1	0.035	20.6	20.6	610.5	104.05