Chapter
10

Erosion and Reservoir Sedimentation

10.1 INTRODUCTION

Erosion, transportation and deposition of sediment in a watershed are natural processes which are intimately connected with the hydrologic processes. Soil and water conservation in watershed and reservoir sedimentation are important parameters affecting the success and economy of many water resources development activities in a basin. This chapter briefly deals with erosion, sediment yield and reservoir sedimentation aspects of the erosion phenomenon. This chapter is only a brief introduction to the topic. For details excellent treatises are available and Refs 2 and 5 contain some valuable source material on this topic.

Erosion is the wearing away of land. Natural agents such as water, wind and gravity are eroding the land surface since geologic times. Out of many erosion causing agents the role of water in detachment, transportation and deposition is indeed very significant. Since recent past, human activities like agricultural practice, mining, building activities, railway and road construction are contributing significantly to erosion of land surface. Water storage structures like reservoirs, tanks and ponds act as receptacles for deposition of eroded material.

10.2 EROSION PROCESSES

Processes

Erosion takes place in the entire watershed including the channels. During a rainfall event, when rain drops impact on a soil surface, the kinetic energy of the drops breaks the soil aggregates and detaches the particles in the impact area. The detached particles are transported by surface run off. Depending upon the flow conditions, topography and geometry of the channel etc. there may be some deposition of the eroded material enroute. Erosion takes place in various modes, which can be classified as follows:

Inter-Rill Erosion In this the detached particles due to raindrop impact are transported over small distances in surface flow of shallow depth without formation of elementary channels called *rills*. The mode of transport is essentially *sheet flow* and the inter-rill erosion from this mode is known as *sheet erosion.* Sheet erosion removes a thin covering of soil from large areas, often from the entire fields, more or less, uniformly during every rain which produces a run-off. The existence of sheet erosion is reflected in the muddy colour of the run-off from the fields.

Rill Erosion Rills are elementary channels which form during the surface runoff event due to the concentration of flow. These are temporary features and facilitate channelling of overland flow. The flow in rills cuts the surface, detaches and transports the sediment in surface runoff.

Gulley Erosion Gullies are formed due to confluence of many rills and formation of a major rill. When a major rill becomes deeper and steeper a gulley is formed. Gullies are capable of transporting larger amounts of sediment. The sediment removed due to formation, enlargement and deepening of gullies is known as *gulley erosion*. Enlarged gullies become permanent topographic features. Gullies are the most visible evidence of the destruction of soil. The gullies tend to deepen and widen with every heavy rainfall. Further, they cut up large fields into small fragments and, in course of time, make them unfit for agricultural operations.

Channel Erosion Channels are permanent topographic features formed due to confluence of gullies. Channel erosion includes stream bed and bank erosion and flood plain scour. Channel erosion is significantly larger than sheet erosion.

Factors Affecting Erosion

The quantity of sediment that is produced by erosion in a watershed depends upon a host of factors related to climate, soil, topography soil cover and human activities in that watershed. The major effects of these parameters are summarized in Table 10.1.

Table 10.1 Factors Affecting Erosion

Factor	Parameter	Effect
Climate	Rainfall intensity	Splash erosion
	Duration of rainfall	Flow erosion
	Temperature	Weathering action
Soil Characteristics	Soil Mass characteristics (Granulation, Porosity, Moisture content)	Infiltration and Runoff rates and hence erosion rate.
	Grain size and shape	Erosion rate and transportation mode.
Topography	Slope (Orientation, Degree and Length)	Steeper slope: Higher energy of flow, higher erosion and transportation rates.
Soil Cover	Vegetation/plant cover	Retardation of flow and erosion rates, Protection from splash erosion.
Land use (Human activities)	Agricultural practice, Mining, Roads, Building construction, etc.	Increased erosion rates
	Reservoirs	Sedimentation

Gross Erosion, Sediment Yield and Delivery Ratio

Gross erosion is the sum of all erosions in watershed. Total sediment outflow from a watershed at a reference section in a selected time interval is known as *Sediment yield*.

Not all the sediment produced due to erosion in a watershed is transported out of it as there will be considerable temporary depositions in various phases and locations. As such, the sediment yield is always less than the gross erosion. The ratio of sediment yield to gross erosion is known as *sediment delivery ratio*.

The sediment yield of a watershed varies with the size of the contributing area. For purposes of comparing the sediment production rate of different areas it is customary to convert the sediment yield data to the yield per unit of drainage area to obtain *sediment–production rate* of the catchment, which is usually expressed in units of tonnes/km^2/year (or in ha-m/km^2/year).

10.3 ESTIMATION OF SHEET EROSION

Estimation of sheet erosion is of utmost importance in soil and water conservation practice and management of watershed. Considering different weightages to the various factors affecting the erosion process, several methods have been proposed to estimate the sheet erosion rate in a watershed. Two popular methods are described below.

Universal Soil Loss Equation (USLE)

The universal soil loss equation is the most widely used tool for estimation of soil loss from agricultural watersheds for planning erosion control practices. The USLE is an erosion prediction model for estimating long term averages of soil erosion from sheet and rill erosion modes from a specified land under specified conditions. The equation is written as

$$A = RKLSCP \tag{10.1}$$

where A = the soil loss per unit area in unit time. Usually the units of A are metric tonnes/ha/year.

R = Rainfall erosivity factor

K = Soil erodibility factor

L = Slope length factor

S = Slope-steepness factor

C = Cover management factor

P = Support practice factor (Ratio of soil loss with a support practice like contouring, strip-cropping or terracing to that with straight row farming up and down the slope).

The various factors of the USLE equation are as below:

Rainfall Erosivity Factor (R) The factor R is the number of rainfall erosion index units (EI_{30}) in a given period at the study location. The rainfall erosion index unit (EI_{30}) of a storm is defined as

$$EI_{30} = \frac{\text{KE} \times I_{30}}{100} \tag{10.2}$$

where KE = Kinetic energy of the storm. The KE in metric tones/ha-cm is expressed as

$$\text{KE} = 210.3 + 89 \log I$$

where I = rainfall intensity in cm/h

I_{30} = maximum 30 minutes rainfall intensity of the storm.

The study period can be a week, month, season or year. The storm EI_{30} values for that length of period is summed up.

Annual EI_{30} values are usually computed from data available at various meteorological stations and lines of equal EI_{30} lines (known as *Iso-erodent* lines) are drawn for the region covered by the data stations for ready use in USLE. Iso-erodent maps of Karnataka and Tamil Nadu are available in Ref. (9). In most parts of Karnataka annual EI_{30} values range from 250 to 500, except in Western Ghats where they range from 500 to 1500. In Tamil Nadu annual EI_{30} values range from 300 to 700.

Soil Erodibility Factor (K) The factor K relates the rate at which different soils erode due to soil properties. These are usually determined at special experimental runoff plots or by use of empirical erodibility equations which relate several soil properties to factor K. Table 10.2 shows some computed values of K at several research stations in the country (Ref. 5).

Table 10.2 Values of K at Several Stations

Station	Soil	Values of K
Agra	Loamy sand, alluvial	0.07
Dehradun	Dhulkot silt, Loam	0.15
Hyderabad	Red chalka sandy loam	0.08
Kharagpur	Soils from lateritic rock	0.04
Kota	Kota-clay loam	0.11
Ootakamund	Laterite	0.04
Rehmankhera	Loam, alluvial	0.17
Vasad	Sandy Loam, alluvial	0.06

[*Source:* Ref. 5]

Topographic Factor (LS) The two factors L and S are usually combined into one factor LS called *topographic factor* and is given by

$$LS = \left(\frac{\lambda}{22.13}\right)^m [65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065] \quad (10.3)$$

where λ = field slope length in metres
m = exponent factor varying from 0.2 to 0.5
θ = angle of slope

Crop Management Factor (C) This factor reflects the combined effect of various crop management practices. Values of factor C for regions surrounding some stations are given in Table 10.3.

Table 10.3 Values of Factor C

Station	Crop	Soil Loss (Tonnes/ha per year)	Value of C
Agra	Cultivated fallow	3.80	1.0
	Bajra	2.34	0.61
	Dichanhium annualtu	0.53	0.13
Dehradun	Cultivated fallow	33.42	1.0
	Cymbopogon grass	4.51	0.13
	Strawberry	8.89	0.27
Hyderabad	Cultivated fallow	5.00	1.0
	Bajra	2.00	0.40

[*Source:* Ref. 5]

Supporting Cultivation Practice (P) This factor is the ratio of soil loss with a support practice to that with straight row farming up and down the slope. Table 10.4 gives the factor P for some support practices.

Table 10.4 Value of Factor P

Station	Practice	Factor P
Dehradun	Contour cultivation of maize	0.74
	Up and down cultivation	1.00
	Contour farming	0.68
	Terracing and bunding in agricultural watershed	0.03
Kanpur	Up and down cultivation of Jowar	1.00
	Contour utilization of Jowar	0.39
Ootacamund	Potato up and down	1.00
	Potato on contour	0.51

[*Source:* Ref. 5]

Use of USLE USLE is an erosion prediction model and its successful application depends on the ability to predict its various factors with reasonable degree of accuracy. Based on considerably large experimental data base relating to various factors of USLE available in USA, this equation is being used extensively in that country to provide reliable estimates of erosion in a variety of situations related to in small agricultural watersheds. It should be noted that to estimate sediment yield of a watershed using USLE, information on sediment delivery ratio of the watershed would be needed.

Based on 21 observed points and 64 estimated erosion values of soil loss obtained by use of USLE at points spread over different regions of the country, Gurmeet Singh *et al* (6) have prepared Iso-erosion rate map of India. Soil erosion rates have been classified by them into 6 categories and the area of the country under different classes of erosion are found to be as shown in Table 10.5.

Table 10.5 Distribution of Various Erosion Classes in India

Range (Tonnes/ha/year)	Erosion Class	Area (km^2)
0– 5	Slight	801,350
5–10	Moderate	1,405,640
10–20	High	805,030
20–40	Very high	160,050
40–80	Severe	83,300
> 80	Very severe	31,895

[*Source:* Ref. 6]

Modified Universal Soil Loss Equation (MUSLE)

The USLE was modified by Williams in 1975 to MUSLE by replacing the rainfall energy factor with a runoff factor. The MUSLE is expressed as

$$Y = 11.8(Q \times q_p)^{0.56}\, K(LS)CP \qquad (10.4)$$

where Y = the sediment yield from an individual storm (in metric Tonnes)
Q = the storm runoff volume in m^3
q_p = the peak rate of runoff in m^3/s
and other factors K, (LS), C and P retain the same meaning as in USLE (Eq. 10.1).

In this equation Q and q_p are obtained by appropriate runoff models (Chapters 5 and 6). In this model Q is considered to represent detachment process and q_p the sediment transport. It should be noted that MUSLE is a sediment yield model and does not need separate estimation of sediment delivery ratio. Also it is applicable to individual storms. It is believed that MUSLE increases sediment yield prediction accuracy. From modelling point of view, MUSLE has the advantage that daily, monthly and annual sediment yields of a watershed can be modelled by combining appropriate hydrologic models with MUSLE.

10.4 CHANNEL EROSION

The channel erosion comprises erosion in bed, sides and also flood plain of the stream. A channel flowing in a watershed transports the runoff that is produced in the catchment and also the erosion products, out of the watershed. The total sediment load that is transported out the catchment by a stream is classified into components depending upon their origin as:

1. Wash load
2. Bed material load
   (i) Bed load (ii) Suspended load

Wash Load

It is sediment originating from the land surface of the watershed and is transported to the stream channel by means of splash, sheet, rill and gully erosion. Wash load is generally composed of fine-grained soils of very small fall velocity.

Bed Material Load

The sediment load composed of grain sizes originating in the channel bed and sides of the stream channel.

Bed Load It is the relatively coarse bed material load that is moved at the bed surface through sliding, rolling, and saltation.

Suspended Load The relatively finer bed material that is kept in suspension in the flow through turbulence eddies and transported in suspension mode by the flowing water is called suspended load. The suspended load particles move considerably long distances before settling on the bed and sides.

In a general sense, bed load forms a small part of total load (usually < 25%) and wash load forms comparatively very small part of the total load. The mechanics of bed material transport in channels, viz. bed load and suspended load have been studied in extensive detail and treatises on the subject are available (for example Ref. 4).

Measurement

While a large number of devices are available for measuring bed load for experimental/special investigations, no practical device for routine field measurement of bed load is currently in use. For planning and design purposes the bed load of a stream is usually estimated either by use of a bed load equation such as Einstein bed load equation[4] or is taken as a certain percentage of the measured suspended load. Table 10.6 gives some recommended values for use in preliminary planning purposes.

Table 10.6 Approximations for Bed Load

Concentration of suspended load (ppm)	Type of material forming the stream channel	Texture of suspended material	Percent of measured suspended load that could be taken as Bed load
Less than 1000	Sand	Similar to bed material	25 to 150
Less than 1000	Gravel, rock or consolidated clay	Small amount of sand	5 to 12
1000 to 7500	Sand	Similar to bed material	10 to 35
1000 to 7500	Gravel, rock or consolidated clay	25 percent sand or less	5 to 12
Over 7500	Sand	Similar to bed material	5 to 15
Over 7500	Gravel, rock or consolidated clay	25 percent sand or less	2 to 8

[*Source:* Ref. 7]

The suspended load of a stream is measured by sampling the stream flow. Specially designed samplers that do not alter the flow configuration in front of the sampler are available. The sediment from the collected sample of sediment laden water is removed by filtering and its dry weight is determined. It is usual to express suspended load as parts per million (ppm) on weight basis as

$$C_s = \left[\frac{\text{Weight of sediment in sample}}{\text{Weight of (sediment + water) of the sample}}\right] \times 10^6$$

Thus the sediment transport rate in a stream of discharge Q m^3/s is

$$Q_s = (Q \times C_s \times 60 \times 60 \times 24)/10^6 = 0.086 Q C_s \text{ tonnes/day}$$

Routine observations of suspended load are being done at many stream gauging stations in the country. At these stations in addition to stream flow discharge Q the suspended sediment concentration and hence the suspended sediment load Q_s is also noted. The relation between Q_s (tones/day) and stream discharge Q (m^3/s) is usually represented in a logarithmic plot (Fig. 10.1) known as *sediment rating curve*. The relationship between Q_s and Q can be represented as

$$Q_s = K Q^n \qquad (10.5)$$

where the exponent is usually around 2.0.

The sediment rating curve in conjunction with the stream flow hydrograph can be used to estimate the suspended sediment load transport in the stream in a specified

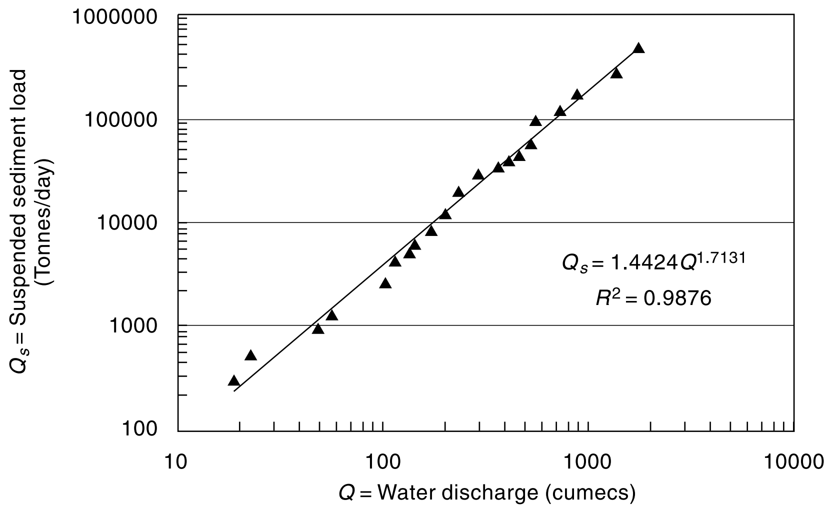

Fig. 10.1 Sediment rating curve (Schematic)

time interval. However, it should be remembered that due to inherent inaccuracies the sediment load obtained by using sediment rating curve is less accurate than that obtained by observed flow hydrograph and sediment concentration data at the gauging station. A method of estimating the annual sediment yield of a watershed by using the sediment rating curve is described in Sec. 10.6.

10.5 MOVEMENT OF SEDIMENT FROM WATERSHEDS

As indicated earlier not all sediment produced in an erosion process in the watershed is transported out of the catchment in a real time basis. Due to loss of momentum of the converying mechanism, considerable deposition occurs mostly in areas of the catchment with low slope, high roughness or very low velocities due to large expansion of flow area. The ratio of sediment yield to the gross erosion in the watershed, called *sediment delivery ratio* (SDR), is an important parameter in quantitative estimation of sediment yield. The values of average annual SDR vary in a wide range as this parameter depends on a host of parameters. Out of the many parameters the significant ones are: (i) the size of the watershed, (ii) the channel density, and (iii) the relief length ratio.

The size of the watershed play an important role in controlling the deposition opportunities for the eroded sediment, the larger the area larger is the opportunity for the sediment to be deposited in the catchment and hence lower SDR. The relief ratio of the watershed is a measure of the average slope of the watershed and as such higher values of relief ratio can be associated with larger transportation rates and hence larger values of SDR. Similarly the SDR is generally higher for well-defined channel network of higher density as the transportation of erosion products out of the catchment is highly facilitated by such channel networks. The variation of SDR with catchment area and relief can be expressed as

$$SDR = KA^{-m} (R/L)^n \tag{10.6}$$

where A = Watershed area
R = watershed relief (Elevation difference)
L = Watershed length
K, m and n are positive coefficients.

Values of K, m and n applicable to a homogeneous region can be estimated by using observed data from experimental watersheds.

10.6 SEDIMENT YIELD FROM WATERSHEDS

Estimation of sediment yield from a watershed is of utmost importance in the soil and water conservation practice in the watershed and in planning, design and operation of reservoirs. While the procedure for estimation of sediment yield is generally problem specific in view of many practical constraints relating to availability of quality data, a few commonly used procedures are described below.

(1) Flow Duration Curve and Sediment Rating Curve Procedure
(2) Reservoir Sedimentation Surveys
(3) Estimation of Watershed Erosion and Sediment Delivery Ratio

Flow Duration Curve and Sediment Rating Curve Procedure

This procedure uses the sediment rating curve of a stream to operate on the flow duration curve of the stream at the same location to obtain weighted expected daily suspended sediment transport load. This when multiplied by 365 days gives the estimated annual suspended sediment load yield at the site.

The flow duration curve of the stream is developed by using available gauged daily discharge data records of sufficiently long length (Sec. 5.5, Chap. 5). The result is expressed as a graph or a table of exceedence probabilities (in percentages) of levels of daily discharge Q. The sediment rating curve of the steam at the gauging site is prepared by using gauged suspended sediment load Q_s (tonnes/day) and the corresponding daily discharge Q (m^3/s), as described in Sec. (10.4). The sediment rating curve is operated on the flow–duration curve as mentioned below:

- The flow duration curve is considered divided into a large number of sections (say 10–20 sections). The sections need not be uniform and it is desirable to provide more sections at low exceedence probabilities.
- Note the ranges of various intervals and also the mid-point value of each interval, (p_i).
- The discharge value Q_I (cumecs) corresponding to each mid-point value of exceedence, p_i is noted.
- Using the sediment rating curve, the value of suspended sediment load Q_{si} (tonnes/day) corresponding to each Q_i is calculated.
- Expected daily suspended sediment discharge at each probability level p_i is
  $$EQ_{\text{si}} = p_i Q_{\text{si}}.$$
- Total weighted expected daily suspended sediment load $Q_{sd} = \Sigma p_i Q_{si}$
- Expected total annual suspended sediment yield $Y_{ss} = 365 \times Q_{sd}$
- The bed load (Y_b) is calculated either as a percentage of annual suspended load yield (Y_{ss}) as in Table 10.4 or by using appropriate bed load equation.
- Total annual sediment yield at the station $Y = Y_b + Y_{ss}$

Example 10.1 given below explains this procedure.

Example 10.1 *The salient co-ordinates of the flow duration curve of a stream at a gauging station is given below:*

Exceedence Probability range (%)	Mean Daily Discharge at mid-point of the interval (Cumecs)	Exceedence Probability range (%)	Mean Daily Discharge at mid-point of the interval (Cumces)
0.1–1.0	250	40–50	65
1.0–5.0	200	50–65	50
5.0–10.0	160	65–80	40
10.0–15.0	135	80–90	25
15–20	120	90–95	15
20–30	100	95–99.0	10
30–40	80		

The gauging station is at the outlet of a watershed of area 3000 sq. km. The sediment rating curve at the station is given by the relation $Q_s = 0.80\ Q^{1.84}$ where Q_s is the suspended sediment load in tonnes/day and Q = discharge in m^3/s. Estimate (i) the total sediment yield of the watershed by assuming the bed load to be 5% of the suspended load, and (ii) the annual average concentration of suspended load.

SOLUTION: Plot the flow duration curve on a logarithmic plot for using it to determine the discharge corresponding to any chosen exceedence probability through interpolation, if necessary (Fig. 10.2).

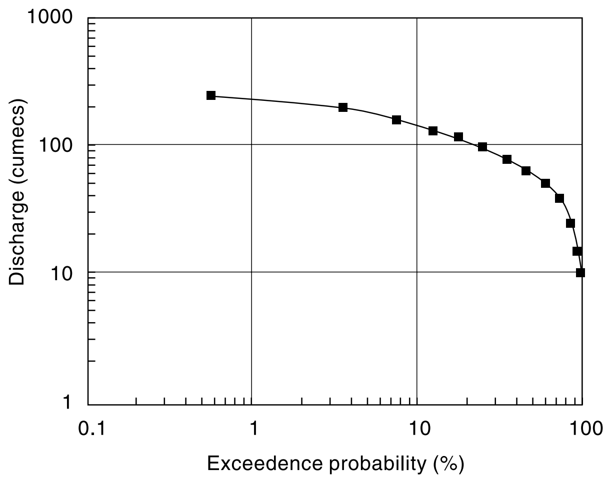

Fig. 10.2 Flow Duration Curve – Example 10.1

Thirteen sections of the flow duration curve are selected and through appropriate interpolations their mid-values of the intervals are read from Fig. 10.2 and values entered in Table 10.7.

The computations are effected in Table 10.7. In this Table

(i) Col. 1 shows the 13 sections into which the exceedence probability is divided.
(ii) Col. 2 is the interval of probability range of Col. 1.
(iii) Col. 3 is the mid-point of interval of Col. 1.
(iv) Col. 4 is the mean daily discharge corresponding to mid point value (Col. 3) and is obtained from flow duration curve, (Fig. 10.2).
(v) Suspended sediment discharge in tonnes/day is calculated for each value of Co1. 4 by using the equation $Q_s = 0.80\ Q^{1.84}$.
(vi) Col. 6 is the Expected daily sediment load of known level of exceedence probability and is obtained as a product of Col. 2 and Col. 5 and divided by 100 to account for percentage values.
(vii) Co1. 7 is the corresponding water flow in units of cumec. day: = [Col. 2 × Col. 4/100]

The total expected mean daily suspended sediment load is 2904 tonnes, obtained as the sum of Co1. 6 values.

Table 10.7 Computation of Suspended Sediment Load

1	2	3	4	5	6	7
Exceedence Frequency range (%)	**Interval (%)**	**Midpoint (%)**	**Mean Daily Discharge (Cumec)**	**Sediment Discharge (tonnes/day)**	**Expected Sediment Load per day (Tonnes)**	**Volume of Water flow (cumec. day)**
					[2] × [5]/100	**[2] × [4]/100**
0.1–1.0	0.9	0.55	250	20668	186.0	2.25
1.0–5.0	4	3.0	200	13708	548.3	8.00
5.0–10.0	5	7.5	160	9092	454.6	8.00
10.0–15.0	5	12.5	135	6651	332.6	6.75
15–20	5	17.5	120	5355	267.8	6.00
20–30	10	25	100	3829	382.9	10.00
30–40	10	35	80	2540	254.0	8.00
40–50	10	45	65	1733	173.3	6.50
50–65	15	57.5	50	1070	160.4	7.50
65–80	15	72.5	40	709	106.4	6.00
80–90	10	85	25	299	29.9	2.50
90–95	5	92.5	15	117	5.8	0.75
95–99.0	4	97.0	10	55	2.2	0.40
				Total	**2904**	**72.65**

Over one year, suspended sediment load yield is = 365 × 2904 = 1,059,960 tonnes.
Thus suspended load yield = 1.06 million tonnes/year.
Bed load (at 5% of suspended load yield) = 0.05 × 1,059,960 = 52998 Tonnes
Total Sediment Yield = 1,112,958 tonnes = say 1.113 million tonnes/year
For a catchment area of 3000 sq.km kill, Sediment yield rate = 1,113,000/3000
= 371 tonnes/sq. km per year.

(ii) Water Yield: Mean daily yield = 72.65 cumec. day
Annual yield = 365 × 72.65 = 26517.25 cumec. days
$= 26517.25 \times (60 \times 60 \times 24)/10^6 = 2291$ million m^3.

Considering annual values

$$\text{Average concentration of Suspended Load} = \frac{1.113 \times 10^6}{(2291 \times 10^6) + (1.113 \times 10^6)} \times 10^6$$

= 485.6
= say **486** parts per million (ppm) by weight.

Reservoir Sedimentation Surveys

Reservoir sedimentation surveys are conducted to get reliable data relating to various aspects of sedimentation such as (i) rate of sedimentation, (ii) sediment densities, (iii) depositional pattern, and (iv) loss of storage capacity of the reservoir at various elevations. The conventional reservoir survey is a hydrologic survey using echo depth recorder along pre-established range lines on the water spread of the reservoir. Depth measurements are taken from a good quality boat with adequate safety provisions by positioning the boat at a desired point on a given range line. The basic measurements are depth of water at the location of the boat and the fixing of the position of the boat with respect to appropriate reference co-ordinates. The depth measurement is done usually by using an echo depth recorder of appropriate accuracy. The position fixing of the boat is through standard land survey techniques through use of *Theodolites*. Nowadays, use of *Total Station* units are very common as it considerably reduces the observational time and computational effort. In addition to the depth and position observations, sediment samples are taken at a number of locations in the reservoir to assess the composition and density of the sediment deposits.

Use of *Differential Global Positioning System* (DGPS) along with an echo recorder in the boat enables faster data acquisitioning with better accuracy. Details of the DGPS methodology adopted by CWC are given in Ref. (1).

The data from a reservoir survey is analyzed to produce contour map of the bed of the reservoir. Some of the end products of the analysis of reservoir survey data are

- Area–Elevation–Capacity curve of the reservoir
- Description of deposition pattern (Qualitative and quantitative)
- L-section of the delta deposition
- Sediment density at key locations
- Average sediment yield from the catchment during the interval between two successive surveys.

Periodic reservoir surveys are essential to efficient management of major reservoirs.

Using remote sensed images of the reservoir taken at frequent intervals in monsoon and non-monsoon periods, the areal extent of the water spread at various elevations can be established very accurately. Further, using the observed reservoir levels corresponding to the date and time of the images, the area elevation capacity curve of the reservoir covering a substantial portion of the reservoir can be established by back office computations only. It may be noted that the reservoir levels are routinely observed at dam site in all reservoirs. This procedure of using remote sensed images is extremely useful in monitoring reservoir sedimentation and efficacy of catchment soil conservation practice.

Estimation of Watershed Erosion and Sediment Delivery Ratio

For very small watersheds having predominantly agricultural land use, the sediment yield can be calculated by using USLE or MUSLE with appropriate factors applicable to the site. If USLE is used the sediment delivery ratio (SDR) will have to be estimated. When regional relations for SDR are not available, SDR applicable to the site will have to be established by empirical equations calibrated by using local information and observed values. The sediment yield is obtained by multiplying gross watershed erosion by SDR.

Empirical Equations

Many empirical equations and procedures have been developed for estimating sediment yield at the outlet of a watershed. A few of these in common use in India or developed by use of Indian data are given below:

Khosla's Equation (1953) (Ref. 8) The annual sediment yield on volume basis is related to catchment area as:

Annual sediment yield rate (on volume basis)

$$q_{sv} = \frac{0.00323}{A^{0.28}} \qquad \text{Mm}^3/\text{km}^2/\text{year} \qquad (10.7a)$$

or Volume of sediment yield per year from the catchment is

$$Q_{sv} = 0.00323\, A^{0.72} \qquad \text{Mm}^3/\text{year} \qquad (10.7b)$$

where A = area of catchment in km^2.

This equation is in common use in many parts of the country to estimate the annual sediment volume inflow into a reservoir. The observed data of Khosla had an upper average limit of 3.6 ha.m/100 sq.km and the absolute maximum limit of observed data was 4.3 ha.m/100 sq.km. While this equation has been used in many of the reservoirs in the country up to about 1970, the observed data of actual sedimentation of many reservoirs indicate that the Eq. 10.7(a) underestimates the sedimentation rate.

Joglekar's Equation (1960): (Ref. 8) Based on data from reservoirs from India and abroad, Joglekar expressed the annual sediment yield rate as

$$q_{sv} = \frac{0.00597}{A^{0.24}} \qquad \text{Mm}^3/\text{km}^2/\text{year} \qquad (10.8a)$$

or Volume of sediment yield per year from a catchment area is

$$Q_{sv} = 0.00597 A^{0.76} \qquad \text{Mm}^3/\text{year} \qquad (10.8b)$$

In these equations A = area of catchment in km^2.

Dhruv Narayan et al's Equation (1983): (Ref. 3) In this annual sediment rate is related to annual runoff as

$$Q_s = 5.5 + 11.1\, Q \qquad (10.9)$$

where Q_s = annual sediment yield rate in tonnes/year from the watershed
Q = annual runoff volume in M.ha.m

Garde and Kothyari's Procedure A detailed procedure for sediment yield estimate for Indian catchments has been developed by Garde and Kothyari[3] (1987). Reference 3 contains a map of India with iso-erosion lines (in tonnes/km^2/year) developed by using this procedure.

10.7 TRAP EFFICIENCY

Deposition Process

When a river enters a reservoir it suffers a massive enlargement of cross section of flow and consequently a large reduction of flow velocity results. The heavy sediment particles are deposited at the mouth of the reservoir in the form of a delta deposit. The sands and gravels are deposited first and the finer particles are deposited farther downstream. The sediment deposits could be classified as *top set beds*, *foreset beds* and *bottomset beds*. The topset beds are composed of coarse sediments of large particle size and foreset beds are of coarse sandy particles. Bottomset beds are of fine particles. Generally topset beds have flat slopes approximately at half the slope of the original channel bed. The foreset slopes are steeper and are about 5 to 7 times steeper than the topset slopes. Delta deposit forms at the mouth of the river entering the reservoir and may cause rising of the backwater profile in the channel upstream of the reservoir. Profile of a typical reservoir delta is shown in Fig. 10.3.

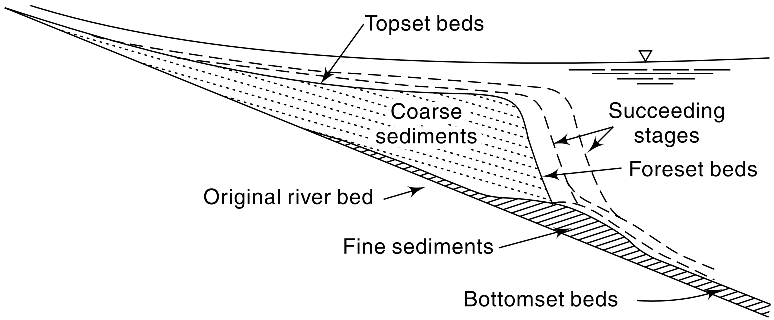

Fig. 10.3 Schematic Representation of Reservoir Delta

Very fine particles of clays and colloids remain suspended and are transported to the remaining parts of the reservoir. The reservoir acts as a sedimentation tank and the suspended particles settle down gradually in course of time depending upon their settling velocities and reservoir operation. In the process of overflow and reservoir withdrawals, some suspended sediment passes out of the reservoir to downstream locations.

Sometimes river water containing high levels of fine to very fine sediment behaves like a high density fluid and flows at the bottom of the reservoir as a gravity current with its own identity. Such flows termed *density currents* or *turbidity currents,* generally move very slowly causing a layer of high density sediment matter suspension at the reservoir bed. The bottom layers of this gradually gets compacted over a long length of time.

Trap Efficiency

Out of the total quantity of sediments brought to the reservoir through the channel system of the catchment a major portion of the sediment is deposited in the reservoir and the balance is moved downstream by overflow and reservoir withdrawals. The amount of sediment trapped in the reservoir is of importance in the long term planning and operation of the reservoir. The ability of a reservoir to trap and retain incoming sediment is known as *trap efficiency* and is usually expressed as a percent of sediment yield of the catchment retained in the reservoir.

Trap efficiency of a reservoir depends on a host of parameters the important ones being (a) sediment characteristics, (b) detention–storage time, (c) nature of outlets, and (d) reservoir operation. As such, the trap efficiency becomes reservoir specific. However, for planning purposes the correlation of trap efficiency with capacity—Inflow ratio (C/I) of the reservoir, developed by Brune[2] is commonly used. Figure 10.4 shows the median and envelope curves for normal ponded reservoir relating the trap efficiency (η_t) with C/I ratio. Brune developed these curves on the basis of observed data from 40 reservoirs covering C/I values ranging from 0.0016 to 2.00.

Figure 10.4 shows that for the median curve $\eta_t \approx 100\%$ for $C/I > 0.70$. For ranges smaller than 0.70, the trap efficiency can be expressed as

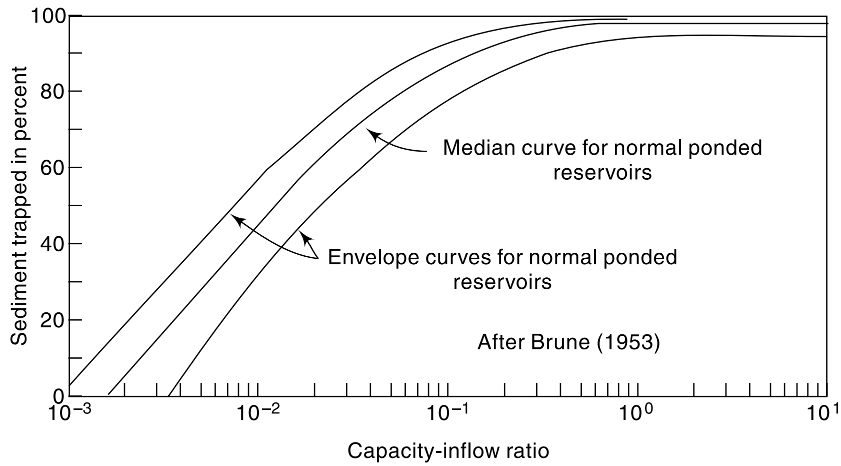

Fig. 10.4 Brune's Curve of Trap Efficiency of a Reservoir

$$\eta_t = K \ln(C/I) + M \tag{10.10}$$

where η_t = trap efficiency in percent

C/I = Capacity –inflow ratio where C = Capacity of reservoir at FRL in Mm^3

and I = annual inflow into reservoir in Mm^3

K and M are coefficients dependent on C/I.

C/I	K	M
0.002 to 0.03	25.025	158.61
0.03 to 0.10	14.193	119.30
0.10 to 0.70	6.064	101.48

10.8 DENSITY OF SEDIMENT DEPOSITS

Sediment load whether computed by equations or by direct observations are usually expressed in terms of its dry weight basis. However, to estimate the volume occupied by a given weight of sediment, it is necessary to know the unit weight of deposited sediment. The unit weight (also known as *specific weight*) is expressed as the ratio of dry weight of the sediment (say tonnes) in unit volume (say in m^3) of the sediment deposit in the reservoir. The unit weight or sediment deposits varies over a wide range depending upon the composition, reservoir operation and consolidation undergone by the deposit over time. Typical values lie in the range of 0.3 to 2.0 tonnes/m^3, with an average of around 1.3 tonnes/m^3. Since sediment deposited in a reservoir gets compacted during time period through a consolidation process, the unit weight increases with time logarithmically. A commonly used formula for rough estimation of unit weight is due to *Koelzer* and *Lara* and is given by

$$W_T = \frac{P_{sa}}{100}(W_1 + B_1 \log T) + \frac{P_{si}}{100}(W_2 + B_2 \log T) + \frac{P_{cl}}{100}(W_3 + B_3 \log T) \tag{10.11}$$

in which W_T = unit weight of deposit of age T years

p_{sa}, p_{si} and p_{cl} = percentage of sand, silt and clay, respectively, on weight basis present in the sediment deposit.

W_1, W_2 and W_3 = unit weight (dry) of sand, silt and clay, respectively, at the end of the first year.

B_1, B_2 and B_3 = constants relating to compacting characteristics of the sediment components.

T = age of sediment in years.

Typical values of the parameters given by Koelzer and Lara are given in Table 10.8.

Table 10.8 Values of Coefficients W and B in Eq. 10.11

Reservoir operation	Sand		Silt		Clay	
	W_1 (kg/m^3)	B_1	W_2 (kg/m^3)	B_2	W_3 (kg/m^3)	B_3
Sediment always submerged or nearly submerged	1490	0	1040	91.3	480	256.3
Normally a moderate reservoir drawdown	1490	0	1185	43.3	737	171.4
Normally considerable reservoir drawdown	1490	0	1265	16.0	961	96.1
Reservoir normally empty	1490	0	1315	0	1250	0

[*Source:* Ref. 8]

Using Eq. 10.11, the average unit weight of deposit W_{av} during a period of T years is obtained as

$$W_{av} = W_{T1} + 0.4343 B_w \left[\left\{ \left(\frac{T}{T-1} \right) \ln T \right\} - 1 \right] \qquad (10.12)$$

where W_{T1} = initial unit weight in tonnes/m^3

and B_w = weighted value of B in Eq. (10.11) in decimal, weightages being fraction of sand, silt and clay in the sample

$= (p_{sa} \cdot B_1 + p_{si} \cdot B_2 + p_{cl} \cdot B_3)/100$

The average unit weight value W_{av} is used in estimating the time period required to reduce the capacity by a defined fraction due to sedimentation. The value of W_1, W_2 and W_3 as well as B_1, B_2 and B_3 used by different agencies differ over a wide margin. As such the values of Table 10.7 are only indicative values. Reference (7) contains valuable data pertaining to unit weights of sediments of many Indian reservoirs.

In estimating the time required for a certain capacity of a reservoir to be filled up by sediment, a trial and error and step-wise procedure is adopted. Example 10.4 illustrates the method.

EXAMPLE 10.2 *Assuming the relative density of a sand particle as 2.6 and unit weight (dry) of a cubic metre of sediment as 980 kg, estimate the weight of 1 m^3 of deposited sediment in the reservoir bed.*

SOLUTION: In 1 m^3 of sediment

Volume of solids = $(1 - p)$ m^3 where p = porosity.

Volume of water = p m^3

Weight of solids = 980 = $(1 - p) \times 2.60 \times 1000$

Hence $p = 0.623$

Weight of 1 m^3 of sediment deposit $= (1 - 0.623) \times 2.60 \times 1000 + 0.623 \times 1000$

$= 980 + 623 = 1603$ kg.

Example 10.3 *Estimate the unit weight of a reservoir sediment in the first year of its deposition if the sediment contains 20% sand, 35% silt and 45% clay by weight. Estimate the volume occupied by 1000 tonnes of sediment in the first year and in 50th year. The reservoir can be assumed to have normally a moderate drawdown. Assume the reservoir operation is such that the sediment is always submerged.*

Solution: The unit weight (dry) of reservoir sediment deposit is given by Eq. (10.11) as

$$W_T = \frac{P_{sa}}{100}(W_1 + B_1 \log T) + \frac{P_{si}}{100}(W_2 + B_2 \log T) + \frac{P_{cl}}{100}(W_3 + B_3 \log T)$$

Here $p_{sa} = 20$, $p_{si} = 35$ and $p_{cl} = 45$

Referring to Table 10.7, values of coefficients B_1, B_2 and B_3 and W_I, W_2 and W_3 are found and introduced into Eq. (10.11) to obtain

$$W_T = \frac{20}{100}(1490) + \frac{35}{100}(1185 + 43.3 \log T) + \frac{45}{100}(737 + 171.4 \log T)$$

$$W_T = 1044.4 + 92.285 \log T$$

When $T = 1$ year, $W_{T1} = 1044.4$ kg/m^3

When $T = 50$ year, $W_{T50} = 1201.2$ kg/m^3

volume of 1000 tonnes of sediment in first year $V_1 = \dfrac{1000}{1044.4/1000} = 957.5$ m^3

in 50th year $V_{50} = \dfrac{1000}{1201.2/1000} = 832.5$ m^3.

Example 10.4 *A reservoir has a capacity of 130 Mm^3 at its full reservoir level. The average water inflow and average sediment inflow into the reservoir are estimated as 200 Mm^3/year and 2.00 M tonnes/year respectively. The sediment inflow was found to have a composition of 30% sand, 30% silt and 40% clay. Estimate the time in years required for the capacity of the reservoir to be reduced to 50% of its initial capacity. Assume the sediment is always submerged.*

Solution: Initial reservoir capacity = 130 Mm^3

Final reservoir capacity = 0.5 × 130 = 65 Mm^3

Amount of sediment deposit = 65 M tonnes

First trial of average unit weight:

Assume a unit weight of 1.0 t/m^3.

Volume of total sediment deposit = 65 Mm^3

Assuming a C/I ratio > 0.70 throughout and trap efficiency $\eta_t = 100\%$

Approximate time required to fill 50% of initial capacity = 65/2.0 = 32.5 years

Assume $T = 33$ years to calculate W_{av}

Second Trial: Using Table 10.7,

Initial unit weight $W_1 = (1490 \times 0.30) + (1040 \times 0.30) + (480 \times 0.40) = 951$ kg/m^3

= 0.951 tonnes/m^3

$B_w = (p_{sa} B_1 + p_{si} B_2 + p_{cl} B_3) = [0 + (0.3 \times 91.3) + (0.4 \times 256.3)] = 129.9$ kg/m^3

By Eq. 10.12

$$W_{av} = 951 + 0.4343 \times (129.9)\left[\left\{\frac{33}{32}\ln 33\right\} - 1\right] = 1096 \text{ kg/m}^3 = 1.096 \text{ tonnes/Mm}^3$$

The calculation for estimating the time to fill 65 Mm^3 of capacity by sediment is performed in tabular form (Table 10.9).

Table 10.9 Computation of Time for filling Part Capacity by Sediment

1	2	3	4	5	6	7	8	9
					Second Trial		Third Trial	
Capacity C (in Mm^3)	ΔC	Capacity-Inflow ratio (C/I)	Trap Efficiency η_t	Average Trap Efficiency $\bar{\eta}_t$	Volume of Sediment Deposited per year	Time to fill ΔC (in years)	Volume of Sediment Deposited per year	Time to fill ΔC (in years)
130		0.650	98.87					
115	15	0.575	98.12	98.50	1.797	8.35	1.78	8.41
105	10	0.525	97.57	97.85	1.786	5.60	1.77	5.64
95	10	0.475	96.97	97.27	1.775	5.63	1.76	5.67
85	10	0.425	96.29	96.63	1.763	5.67	1.75	5.71
75	10	0.375	95.53	95.91	1.750	5.71	1.74	5.76
65	10	0.325	94.66	95.10	1.735	5.76	1.72	5.80
					Total	36.73	Total	37.00

In Table 10.9:

Co1. 1 gives the capacity of the reservoir. The decrease in the capacity due to sedimentation is considered in 6 steps. (Note that the steps need not be equal.)

Col. 2 is the decrease in capacity between two successive steps.

Col. 3 is the Capacity – Inflow ratio at the beginning of the step. Col. 3 = (Col. 1)/200

Col. 4 is the trap efficiency corresponding to C/I value of Col. 3 calculated by using Eq. (10.10). Thus Col. 4 = 6.064 × ln (Co1. 3) + 101.48

Col. 5 is the average trap efficiency in a step

Col. 6 is the volume of sediment deposited in the reservoir per year during the event represented by the step. Co1. 6 = 2.00 × ((Col. 5)/100)/1.096

Col. 7 is the time in years required to fill the capacity represented by the step.
Col. 7 = Col. 2/Co1. 6.

The sum of the time periods represented by Col. 7 is the time required to fill the capacity by 65 Mm^3. Thus the total time required to reduce the reservoir capacity by 50% is T_{50} = 36.73 years = say **37 years**.

Since the value of T_{50} differs from the assumed value of 33 years by more than 5% further trials to refine the value of W_{av} are necessary.

Third trial: Take T = 37 years

$$W_{av} = 951 + 0.4343 \times (129.9) \left[\left\{\frac{37}{36}\ln 37\right\} - 1\right] = 1104 \text{ kg/m}^3 = 1.104 \text{ tonnes/Mm}^3$$

Using this value of W_{av} = 1.104 tonnes/Mm^3 Second Trial of Table 10.8 is refined as shown in Cols. 8 and 9 of Table 10.8.

The total time required for filling 50% of capacity is indicated as 37 years which is the same as assumed at the beginning of this trial. Thus $\boldsymbol{T_{50}}$ **= 37 years** is the desired period.

10.9 DISTRIBUTION OF SEDIMENT IN THE RESERVOIR

Classification of Reservoirs

When a sediment laden stream enters a reservoir, the sediment is deposited not only at the head of the reservoir as delta deposit but also all along the internal surface of the reservoir. The area as well as the volume distribution of accumulated sediment at various levels is an important factor in the design of reservoirs. Further, the distribution and the rate of growth of deposits decide the location of various outlets as well as the operation strategy of the reservoir.

The deposition pattern of sediment depends on a host of factors which include the slope, geometry of the reservoir, particle size distribution of sediment and the operation pattern of the reservoir. On the basis of extensive field data of reservoirs in USA, Borland and Miller classified the reservoir into four standard types as mentioned below:

Classification Number	Reservoir Type	Parameter *m*
IV	Gorge	1.0–1.5
III	Hilly region	1.5–2.5
II	Flood plain, Foot-hill region	2.5–3.5
I	Lake	>3.5

The parameter *m* is the reciprocal of the slope of best fitting line obtained by plotting reservoir elevation above bed as ordinate and reservoir capacity at that elevation as abscissa on a log-log paper [Fig. 10.5(a)]. (Note that linear scales are used to measure the slope). The typical distribution of sediment in these four types of reservoirs is shown in Fig. 10.5(b).

It is seen that Type I reservoirs have considerably lower percentage of silt at lower depths when compared to Type IV reservoirs. Conversely, Type IV and III reservoirs have very low percentage of sediment at top portions when compared to Type I and II reservoirs.

Methods of Predicting Sediment Distribution

Two methods, both suggested by Borland and Miller, known as (i) *Empirical area reduction method* and (ii) *Area increment method* are in common use. These are described below.

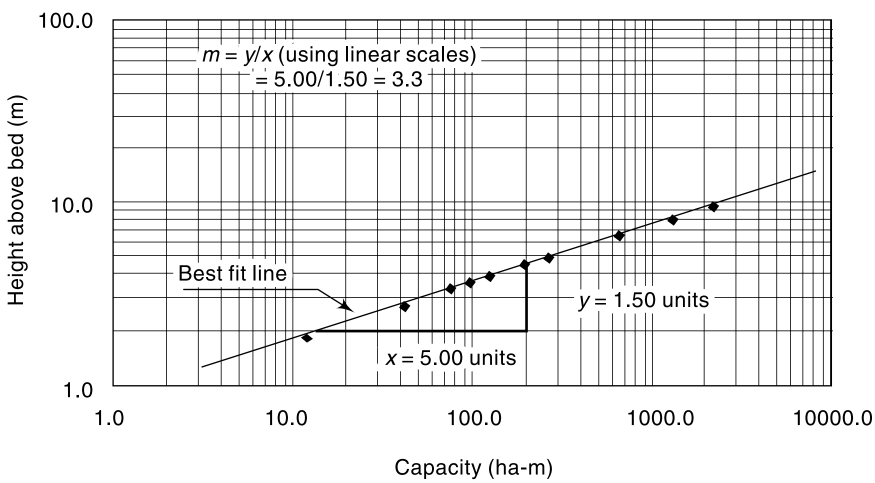

Fig. 10.5(a) Determination of Parameter *m*

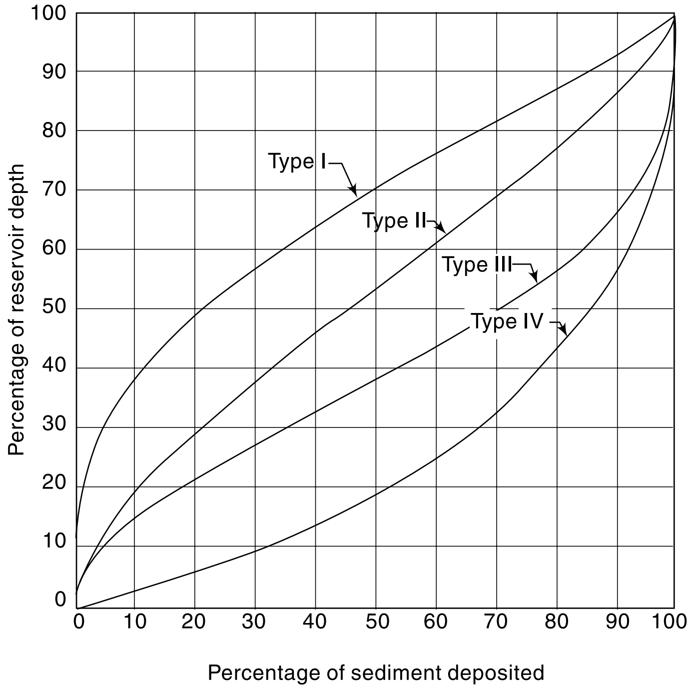

Fig. 10.5(b) Typical Distribution of Sediment in various Reservoir Types

EMPIRICAL AREA REDUCTION METHOD

(a) Data Needed

1. Elevation – Area – Capacity relationship for the reservoir at any time T_i after the construction of the reservoir. Usually at $T_i = 0$, i.e. at the start of the reservoir project this data will be available.
2. Estimated volume of sediment V_s to be deposited in a period $(T_f - T_i) = \Delta T$ years. Usually for design purposes $\Delta T = 50$ years or 100 years is selected.

(b) Distribution Pattern Based on the observed reservoir sediment distribution data, Borland and Miller have expressed the distribution of sediment area at any level h above the bed as

$$A_p = C\ p^{m_1} (1 - p)^{n_1} \tag{10.13}$$

where A_p = a dimensionless relative area = $\dfrac{\text{Area at elevation } h \text{ above the bed}}{\text{Area at initial zero elevation}}$

p = relative depth = h/H

where h = height above the reservoir bed to any given elevation in the reservoir, and

H = Difference in the elevations of FRL and original bed of the reservoir = depth or reservoir at Full reservoir level (FRL). (Obviously, p has a range of 0 to 1.0.)

C, m_1 and n_1 = coefficients dependent on the Type classification of the reservoir as given below (Ref. 7):

Reservoir Type	C	m_1	n_1
I	5.074	1.85	0.36
II	2.487	0.57	0.41
III	16.967	1.15	2.32
IV	1.486	–0.25	1.34

(c) Procedure A trial and error procedure is adopted. The reservoir surface can be taken to be somewhat conical in shape. When a sediment volume V_s is deposited gradually over a time ΔT, some part of the conical portion of the reservoir completely fills up with sediment (say up to a height of h_o above the vertex) and in the remaining portion the deposition will be on the surface and the cross sectional area at any elevation will be diminished, Fig. 10.6. Let the volume of sediment filled in the conical portion to a depth of $h_o = V_{so}$.

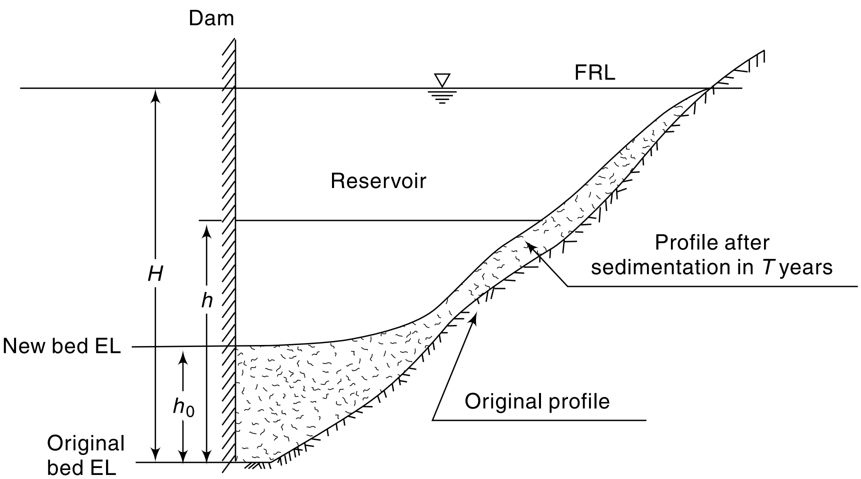

Fig. 10.6 Definition Sketch

1. The elevation h_o, relative to the original bed of the reservoir, up to which the sediment completely fills up the reservoir, is assumed. The top of this filled up portion is taken as the new datum, i.e., the new zero elevation. The area A_o at this depth is determined. The value of p at this level = $p_o = h_o/H$.
2. The new total depth of the reservoir = $H - h_o$
3. Volume of sediment to be distributed = $V_s - V_{so}$
4. The type classification of the reservoir is determined
5. Values of A_p are determined for various values of p (= h_o/H) by using Eq. (10.13)
6. At $p = p_o$, $A_p = A_{po}$
7. Find $K = A_o/A_{po}$
8. Using this value of K, the sediment area A_s at any height h above, the new datum is determined as $A_s = A_pK$
9. ΔV_s = Volume or sediment deposited between two consecutive heights h_1 and h_2 above the new datum is determined either as

$\Delta V_s = (A + A_2)\, \Delta h/2$ …(average end area method) or as

$\Delta V_s = (A_1 + A_2 + \sqrt{A_1 A_2})\dfrac{\Delta h}{3}$ …(weighted area method).

where $\Delta h = (h_2 - h_1)$

10. Accumulated sediment at various elevations starting from the original bed elevation are now determined.
11. The total volume of deposited sediment up to the top of the reservoir, obtained at step No. 10, must be equal to the given value of V_s. If the value found in step 10 differs from V_s considerably, say more than 2%, then the entire procedure is repeated by assuming a new value of h_o, i.e. new zero elevation.

Example 10.5 given below illustrates the use of this procedure.

Example 10.5 *For a reservoir the capacity – area – elevation data is given below. Estimated total accumulation of sediment in the reservoir in 50 years of its operation is 100 MCM. Original bed elevation is El. 535.00 m and the spillway crest is at 546.50 m. Determine the distribution of 100 MCM of sediment in the reservoir by the empirical area reduction method. The reservoir can be taken as of Type II. [Note: For the first trial assume the level up to which the reservoir is fully covered by sediment at the end of 50 years as 539.40 m].*

Elevation (m)	535.00	536.50	538.0	539.0	539.40	540.00
Original Water spread area (sq. km)	2.0	4.51	6.89	8.71	11.52	15.74
Original Reservoir Capacity (MCM)	0	5.18	13.13	20.92	24.96	33.10
Elevation (m)	541.00	542.00	543.00	544.00	545.00	546.50
Original Water spread area (sq km)	26.88	38.02	47.84	57.66	67.09	81.15
Original Reservoir Capacity (MCM)	54.35	86.76	244.76	355.97	744.76	355.97

Solution: Table 10.10 shows the computations.

First the given Elevation-area data is enlarged through linear interpolation to cover the elevation at an average interval of 0.50 m. The incremental area between two area elements A_1 and A_2 separated by a height Δh is calculated as

$$\Delta V = \frac{(A_1 + A_2)}{2} \times \Delta h$$

The accumulated volume starting from the original bed El. 535.00 m is calculated to get original reservoir capacity – elevation data.

In Table 10.9:

Col. 2 = Elevation in metres

Col. 3 = Original water surface area at given elevation, sq.km

Col. 4 = Height above original bed elevation = [Elevation of the item – 535.00] = h

Col. 5 = Original reservoir capacity in MCM. This list contains given data as well as newly generated data

Col. 6 = Relative depth $p = h/H$ = Col. 4 /11.50

Col. 7 = Function A_p calculated by Eq. 10.13 as $A_p = 2.487\, p^{0.57} (1 - p)^{0.41}$.

Table 10.10 Empirical Area Reduction Method of Determining Sediment Deposition—Example 10.6

Sediment Deposition Computations by Empirical Area Reduction Method
Period of Sedimentation: 50 years
Total Sedimentation accumulation in the period: 100 MCM
Spillway crest: 546.50 m | **Original River bed = 535.00** | **Depth up to spillway crest = 11.50 m**
First Trial (K_1 = 9.761) | **Final Trial (K_2 = 9.646)** | **Final Values**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Sl. No.	Elevation (m)	Original Water spread Area (sq. km)	Height above original bed (m)	Original Reservoir Capacity (MCM)	Relative Depth (p)	Function *A* (Type II)	Sediment Area (KA_P) (Sq. km)	Incremental sediment volume (MCM)	Accumulated Sediment Volume (MCM)	Revised Sediment Area (KAp) (sq. km)	Revised Incremental Sediment Volume (MCM)	Revised Accumulated Sediment Volume (MCM)	Reservoir Area at the end of 50 years (Sq. km) (MCM)	Reservoir Capacity at the end of 50 years (MCM)	Available reservoir elevation after at the end of 50 years
1	535.0	2.00	0.00	0.00	0	0									
2	535.5	2.77	0.50	1.19	0.043	0.409									
3	536.0	3.55	1.00	2.76	0.087	0.595									
4	536.5	4.35	1.50	4.73	0.130	0.735									
5	536.6	4.51	1.60	5.18	0.139	0.760									
6	537.0	5.16	2.00	7.11	0.174	0.848									
7	537.5	6.02	2.50	9.90	0.217	0.942									
8	538.0	6.89	3.00	13.13	0.261	1.021									
9	538.5	7.80	3.50	16.80	0.304	1.088									
10	539.0	8.71	4.00	20.92	0.348	1.143									
11	539.4	11.52	4.40	24.96	0.383	1.180	11.52	0.00	24.96	11.52	0.00	24.96	0.00	0.00	539.4
12	539.5	12.22	4.50	26.13	0.391	1.189	11.60	1.16	26.11	11.46	1.15	26.11	0.76	0.03	539.5
13	540.0	15.74	5.00	33.10	0.435	1.224	11.95	5.89	32.00	11.81	5.82	31.92	3.93	1.18	540.0
14	540.5	21.31	5.50	42.33	0.478	1.251	12.21	6.04	38.04	12.07	5.97	37.89	9.24	4.44	540.5
15	541.0	26.88	6.00	54.35	0.522	1.268	12.38	6.15	44.19	12.24	6.08	43.97	14.64	10.38	541.0
16	541.5	32.45	6.50	69.16	0.565	1.277	12.46	6.21	50.40	12.32	6.14	50.11	20.13	19.05	541.5
17	542.0	38.02	7.00	86.76	0.609	1.276	12.45	6.23	56.63	12.30	6.16	56.26	25.72	30.50	542.0

(*Contd.*)

Table 10.10 (*Contd.*)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
18	542.5	42.93	7.50	106.99	0.652	1.264	12.34	6.20	62.83	12.19	6.12	62.39	30.74	44.60	542.5
19	543.0	47.84	8.00	129.67	0.696	1.242	12.12	6.12	68.94	11.98	6.04	68.43	35.86	61.24	543.0
20	543.5	52.75	8.50	154.80	0.739	1.207	11.78	5.97	74.92	11.64	5.90	74.33	41.11	80.47	543.5
21	544.0	57.66	9.00	182.40	0.783	1.157	11.29	5.77	80.68	11.16	5.70	80.03	46.50	102.36	544.0
22	544.5	62.37	9.50	212.40	0.826	1.089	10.63	5.48	86.16	10.50	5.42	85.45	51.87	126.95	544.5
23	545.0	67.09	10.00	244.76	0.870	0.996	9.72	5.09	91.25	9.61	5.03	90.48	57.48	154.28	545.0
24	545.5	71.81	10.50	279.47	0.913	0.868	8.47	4.55	95.80	8.37	4.49	94.97	63.44	184.50	545.5
25	546.0	76.53	11.00	316.55	0.957	0.670	6.54	3.75	99.55	6.47	3.71	98.68	70.06	217.87	546.0
26	546.5	81.15	11.50	355.97	1.000	0.000	0.00	1.64	101.19	0.00	1.62	100.30	81.15	255.67	546.5

Capacity after 50 years = 256 (MCM)

$K_1 = 9.761$

$K_2 = 9.646$

El.539.40 m is the determined new zero elevation after 50 years

First Trial: A trial and error Procedure is adopted. For the first trial, the level up to which the reservoir is fully covered by sediment at the end of 50 years is taken as 539.40 m, as per the suggestion in the problem. This would be the new datum for the bed of the reservoir at the end of 50 years. At this level:
From Col. 7, A_1 = 1.180, 3, From Col. 3, Original reservoir area = A_o = 11.52 km^2.
Coefficient K (for the first trial) = K_1 = 11.52/1.180 = 9.761

Col. 8 = Represents $K A_p$ = 9.761 × Col. 7 for all elevations higher than 539.40 m. This column represents the area covered by sedimentation at a particular level and hence called *Sediment area*.

Col. 9 = Incremental sediment volume between two successive elevation calculated as (average sediment area × incremental depth).

Col. 10 = Accumulated sediment volume starting from 24.96 MCM at El.539.40 m. Note that the value 24.96 represents the original volume of the reservoir at the elevation 539.40 m and this volume is taken as completely filled up by sediment at the end of 50 years.
The last value in Col. 10 is obtained as 101.19 MCM whereas the given sediment data indicates a deposition of 100 MCM in 50 years. This indicates a need for second trial. The calculations are very near the logical final values and since the difference is slightly more than 0.5% only minor corrections are needed. Tweaking the coefficient K does this. Thus for second trial K_2 = Adjusted value of K_1 on a pro-rata basis of total accumulated sediment volume = $\dfrac{K_1 \times 100}{101.19}$ = 9.646. Values of this second trial (with K_2 = 9.646) are shown in Cols. 11, 12 and 13.

Second Trial:

Col. 11 = Revised sediment area with K_2 = 9.646.
Col. 12 = Revised incremental sediment volume with K_2 = 9.646
Col. 13 = Revised accumulated sediment volume with K_2 = 9.646

Note that this second trial improves the result considerably and the accumulated sediment volume at El. 546.50 m is 100.30 MCM. The difference between this and the given value of 100.0 MCM is negligible being less than 0.5% and thus this distribution could be taken as final values.

Col. 14 = Reservoir area distribution at the end of 50 years
Col. 15 = Reservoir volume distribution at the end of 50 years.
Col. 16 = Available reservoir elevations at the end of 50 years.

Note that the new bed level of the reservoir at the end of 50 years is 539.40 m.

The distribution of the area and capacity with elevation, at the beginning and at the end of 50 years is shown in Fig. 10.7 (a and b).

Area Increment Method The basic assumption of this method is that the volume of sediment deposition per unit height in the reservoir is constant. This is same as assuming that the area-elevation curve after sedimentation is parallel to the curve before sedimentation. Thus the sediment area is constant at all elevations and is equal to the sediment area at the new zero elevation, h_0. The distribution of sediment is given by

$$V_s = A_o(H - h_0) + V_0 \qquad (10.14)$$

where V_s = sediment volume to be distributed in the reservoir
A_o = original reservoir area at the new zero level

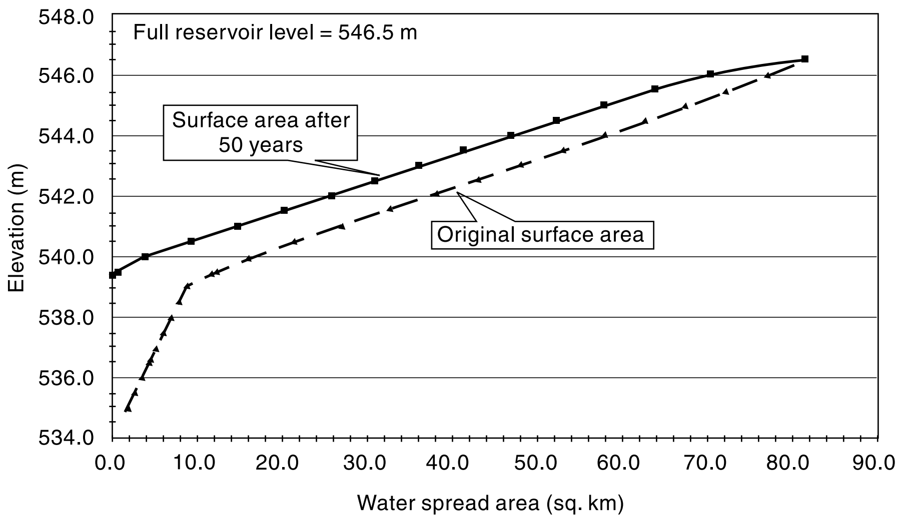

Fig. 10.7(a) Reservoir Elevation – Area Curves—Example 10.6

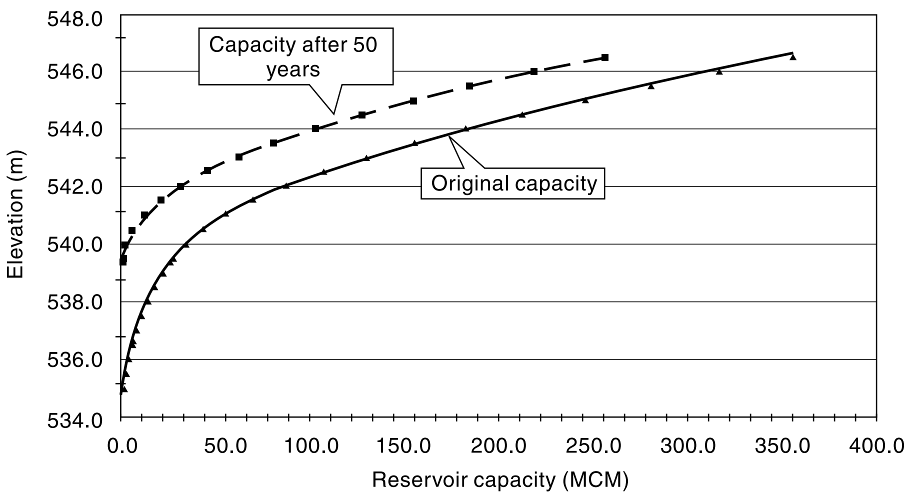

Fig. 10.7(b) Reservoir Elevation – Capacity Curves—Example 10.6

h_o = depth at which reservoir is completely filled up = elevation of new zero elevation with respect to old bed elevation as datum

V_o = sediment volume between old zero and new zero bed level

H = Difference in the elevations of FRL and original bed of the reservoir = depth of reservoir at Full reservoir level (FRL), (original value).

The procedure or distributing the given total sediment volume V_s is done by a trial and error procedure as detailed below:

(i) Assume h_o and find corresponding V_o and A_o

(ii) Check whether V_s given by Eq. (10.14) agree with the given value. If not repeat with a new value of h_o

(iii) Sediment area at any level is A_o. Establish water surface area at any level as (original area – A_o).

(iv) Over a depth Δh. Incremental sediment volume = $A_o \cdot \Delta h$.

Hence reservoir capacity after sedimentation at any level h' above new zero

$$= (\text{Original volume} - V_o - A_o h')$$

Example 10.6 illustrates the procedure

EXAMPLE 10.6 *The reservoir of Example 10.6 is expected to have 50 MCM* of *sediment accumulated in first 25 years of its operation. Determine the distribution of this 25 MCM of sediment by Area Increment method.*

SOLUTION: Given data: $V_s = 50$ Mm^3

$H = 546.50 - 535.00 = 11.50$ m

First Trial:

Assume that the new zero elevation is 536.50 m giving $h_o = 536.5 - 535.00 = 1.50$ m

$A_o = 4.35$ km^2 (from given data. Col. 3 in Table 10.11)

V_o = volume corresponding to El. 536.50 = 4.73 Mm^3 (from Col. 6 of Table 10.11)

By Eq. 10.14 $V_s = V_o + A_o (H - h_o) = 4.73 + 4.35(11.5 - 1.5) = 48.235$ Mm^3

While this value is close to the given value of $V_s = 50$ Mm^3, a new trial to get better agreement is needed.

Second Trial:

For the second trial assume new zero elevation as 535.60 m.

$h_o = 536.6 - 535.00 = 1.60$ m

$A_o = 4.51$ km^2

V_o = volume corresponding to El. 536.60 = 5.18 Mm^3 (From Col. 6 of Table 10.11)

By Eq. (10.14) $V_s = V_o + A_o(H - h_o) = 5.18 + 4.51\ (11.5 - 1.6) = 49.83$ Mm^3

This V_s value is nearly equal to the given value of 50.00 Mm^3 and differs by only 0.34%. Since the difference is less than the permissible 1% value, no new trial is required. The assumed zero elevation of 536.60 is considered to represent the bed elevation at the end of 25 years satisfactorily. Using this value, the distribution of sediment at different elevations is worked out as shown in Table 10.11.

In Table 10.10:

Cols. 2 and 3 are given data. Col. 4 is incremental height in m

Col. 5 is the incremental reservoir capacity between two elevations calculated as (average area × incremental height)

Col. 6 is cumulative value of Co1. 5

Col. 7 is sediment area at chosen h_o and is constant over the full depth of the reservoir measured above the chosen new zero elevation

Col. 8 is incremental sediment volume calculated as equal to [A_o × (incremental height)].

Col. 9 is cumulative sediment volume. Note that the values are the same as in Col.6 up to El. 536.60.

Col. 10 is estimated reservoir area at the end of 25 years. This area starts from new zero elevation of 536.60 m and is equal to (Col. 3–Col. 7).

Col. 11 is estimated reservoir volume at the end of 25 years. This volume starts with a zero value at new zero elevation of 536.60 m and is equal to (Col. 6–Col. 9).

10.10 LIFE OF A RESERVOIR

A reservoir is designed to serve one or more specific purposes. Sedimentation causes progressive reduction in the capacity of the reservoir and this may impact on the de-

Table 10.11 Area Increment Method of determining Sediment Deposition—Example 10.7

Period of Sedimentation: 25 years
Total Sediment accumulation in the period : 50 MCM   Spillway crest: 546.50 m

Sl. No.	Elevation (m)	Water spread Area (sq. km)	Incremental height (m)	Incremental volume (MCM)	Reservoir Capacity (MCM)	Sediment Area $= A_0$ (sq. km)	Incremental Sediment Volume (MCM)	Cumulative Sediment Volume (MCM)	Reservoir area at the end of 25 years (sq. km)	Reservoir Capacity at the end of 25 years (MCM)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	535.0	2.00	0.00	0.00	0.00	0	0	0	0	0.0
2	535.5	2.77	0.50	1.19	1.19	0	0	1.19	0	0.0
3	536.0	3.55	0.50	1.58	2.76	0	0	2.76	0	0.0
4	536.5	4.35	0.50	1.97	4.73	0	0	4.73	0	0.0
5	**536.6**	4.51	0.10	0.44	5.18	4.51	0.00	5.18	0	0.0
6	537.0	5.16	0.40	1.93	7.11	4.51	1.804	6.98	0.65	0.1
7	537.5	6.02	0.50	2.79	9.90	4.51	2.255	9.24	1.51	0.7
8	538.0	6.89	0.50	3.23	13.13	4.51	2.255	11.49	2.38	1.6
9	538.5	7.80	0.50	3.67	16.80	4.51	2.255	13.75	3.29	3.0
10	539.0	8.71	0.50	4.13	20.92	4.51	2.255	16.00	4.20	4.9
11	539.5	12.22	0.50	5.21	26.13	4.51	2.255	18.26	7.71	7.9
12	540.0	15.74	0.50	6.97	33.10	4.51	2.255	20.51	11.23	12.6
13	540.5	21.31	0.50	9.23	42.33	4.51	2.255	22.77	16.80	19.6
14	541.0	26.88	0.50	12.02	54.35	4.51	2.255	25.02	22.37	29.3
15	541.5	32.45	0.50	14.81	69.16	4.51	2.255	27.28	27.94	41.9
16	542.0	38.02	0.50	17.60	86.76	4.51	2.255	29.53	33.51	57.2
17	542.5	42.93	0.50	20.23	106.99	4.51	2.255	31.79	38.42	75.2
18	543.0	47.84	0.50	22.68	129.67	4.51	2.255	34.04	43.33	95.6

(*Contd.*)

(*Contd.*)

1	2	3	4	5	6	7	8	9	10	11
19	543.5	52.75	0.50	25.14	154.80	4.51	2.255	36.30	48.24	118.5
20	544.0	57.66	0.50	27.59	182.40	4.51	2.255	38.55	53.15	143.8
21	544.5	62.37	0.50	30.00	212.40	4.51	2.255	40.81	57.86	171.6
22	545.0	67.09	0.50	32.36	244.76	4.51	2.255	43.06	62.58	201.7
23	545.5	71.81	0.50	34.72	279.47	4.51	2.255	45.32	67.30	234.2
24	546.0	76.53	0.50	37.08	316.55	4.51	2.255	47.57	72.02	269.0
25	546.5	81.15	0.50	39.41	355.97	4.51	2.255	**49.83**	**76.64**	**306.1**

El. 536.60 m is the determined new bed elevation.
Total sediment load up to El. 546.50 m at the end of 25 years = 49.83 = say **50 MCM**

sired performances of the reservoir at some point in time. With this in view, various definitions of specific terms related to the general term *life of a reservoir* are defined.

USEFUL LIFE Period through which deposited sediment does not impact on the intended purposes of the reservoir. Useful life is considered to be over when an additional reservoir is to be built (or water is to imported from another source) to meet the original intended demand.

ECONOMIC LIFE A point of time since the commissioning of the project at which the physical depreciation due to sedimentation, in conjunction with other economic and physical factors cause the operation of the reservoir, to meet intended demands, economically inefficient.

DESIGN LIFE A fixed period (usually 50 years or 100 years) adopted by the designers as estimate of minimum assured useful life.

The present-day practice in India is to adopt 100 years as the design life of the reservoir. The CWC practice in this connection is as follows:

- Volumes of sediment estimated to be deposited in the reservoir in 50 years (V_{50}) and in 100 years (V_{100}) of operation are worked out.
- Distribution of V_{100} is performed and the zero level after sedimentation is established.
- Minimum drawdown level (MDDL) is fixed a little above the zero level corresponding to V_{100} found in second step above
- Distribution of sediment V_{50} is performed to develop area – elevation – capacity curves. This set of curves corresponding to 50 years of sedimentation is used in working-table studies, reservoir performance simulation studies, etc.

10.11 RESERVOIR SEDIMENTATION CONTROL

Sedimentation of reservoirs causes great economic loss primarily due to reduction of storage capacity of the reservoirs. Other impacts of sedimentation such as increased high flood levels due to flattening of the bed slope in the river upstream of the reservoir leading to frequent inundation and water logging in the up-reservoir areas are serious in many instances. As such, monitoring and control of sedimentation forms a prime item in the management of any major reservoir project. Considering the basic natural process of erosion and transportation inherent in the phenomenon, it is obvious that the reservoir sedimentation can never be stopped but with good effort can be retarded considerably. The basic methods available for control can be listed as:

- Reduction in sediment yield from the catchment
- Reduction in the rate of accumulation of sediment in the reservoir
- Physical removal of already deposited sediment

REDUCTION IN SEDIMENT YIELD

Various control measures that can be adopted to reduce erosion and transportation of eroded products in the catchment are dealt under the specialized interdisciplinary practice known as Soil Conservation technology. After a thorough study of the catchment area, soil and water conservation practices best suited for each sub watershed of the catchment have to be established by the specialists in the area of soil and water conservation. In a general sense, the soil conservation practices involve components such as

- Terraces, strip cropping and contour bunding to retard overland flow and hence reduction in sheet erosion
- Check dams, ravine reclamation structures etc. to reduce sediment inflow into the stream
- Vegetal covers, grassed waterways and afforestation to reduce runoff rates and hence to reduce erosion.

In view of the interlocking and interdependency feature of various aspects of soil, water, biomass production and livelihood of people living in the watersheds an integrated approach should be adopted in watershed management. Integrated operation of soil and water conservation aspects in a watershed can be represented as in Fig. 10.8.

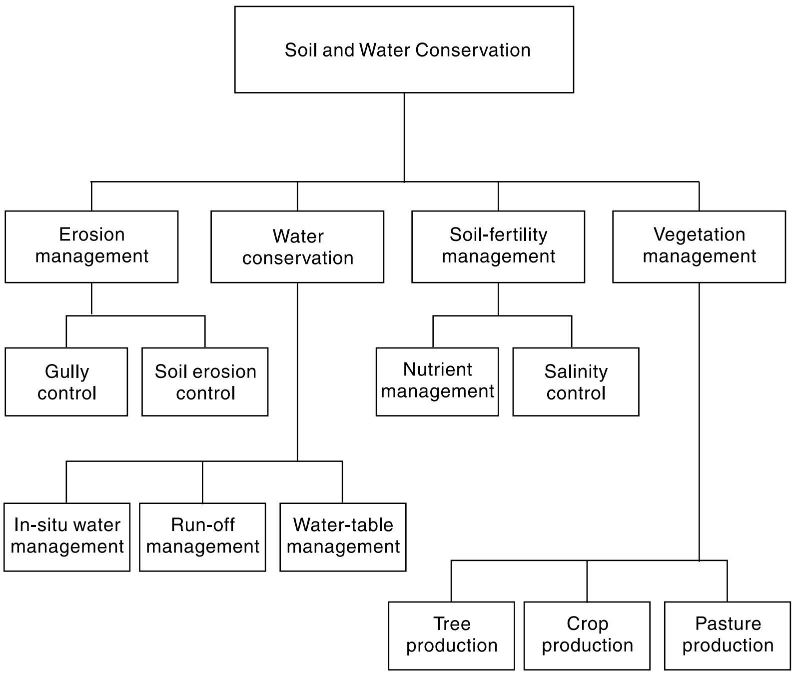

Fig. 10.8 Integrated Soil and Water Conservation

Reduction of Accumulation of Sediment

Accumulation of the sediment that flows into the reservoir can be reduced if arrangements are made for venting out the sediment through structural arrangements in the dam and appropriate reservoir operation. Some of the measures that can be adopted towards this are:

- Provision of scouring sluices at lower elevations in the dam to flush out high concentration sediments and density currents
- Appropriate operation of gated overflow outlets and other sluices in the dam in such a manner to allow passage of freshets with high concentration of sediments to the downstream of the dam and to catch only relatively clear latter flows for storage in the reservoir.

Physical Removal of Deposited Sediments

Deposited sediments can be removed by hydraulic or mechanical means. However, for large reservoirs the disposal of removed sediment does pose environmental problems and also the entire operation may not be economically feasible. However, for many small reservoirs sediment removal, popularly known as *desilting* can be a feasible proposition. As typical example, desilting of irrigation tanks of south India can be cited. Several thousands of tanks in South India, particularly in Andhra Pradesh, Karnataka and Tamil Nadu are in existence since several decades and are serving as sources of minor irrigation. Many of these tanks have been successfully desilted, in recent past, and their capacity restored to their original values. Acute scarcity of water, community participation and use of tank silt as soil amendment in both irrigated command area and in the up-catchment rain-fed agricultural lands have made these ventures economically viable.

10.12 EROSION AND RESERVOIR SEDIMENTATION PROBLEMS IN INDIA

Erosion Problem

The India, practically all the regions are subjected to fairly serious erosion problems due to several reasons. It is estimated that out of 305.9 M ha of reported area in the country about 145 M ha is in need of soil conservation measures. Table 10.12 gives details of soil conservation problem areas in India under different land cover/use. It is seen that major part of agricultural land suffers from erosion problem and consequent loss of productivity, nutrient and soil resource. The distribution of soil erosion problem areas (as of 1985) statewise is shown in Table 10.13(a).

Table 10. 12 Soil Conservation Problem Areas in India

Particulars	Total Area (M ha)	Soil-Conservation problem area (M ha)
Forest	61.170	20
Culturable wasteland	17.362	15
Permanent pastures and other grazing land	14.809	14
Land under miscellaneous tree crops and groves	4.218	1
Fallow lands:		
(i) Fallow lands other than current fallows	9.168	8
(ii) Current fallows	11.132	7
Total for Fallow lands	15	20.5
Net area under cultivation	137.9	80
Other land uses, not available for agriculture, forest, etc.	50.188	—
Grand Total	305.947*	145

*305.947 million hectares is the reported area for land-utilisation statistics out of a geographical area of 328.809 million hectares.

Table 10.13(a) State-wise Distribution of Soil Erosion Problem Areas (as of 1985)

Sl. No.	State	Extent of Problem area due to Soil Erosion (M ha)	Sl. No.	State	Extent of Problem area due to Soil Erosion (M ha)
1.	Andhra Pradesh	11.502	14.	Nagaland	0.405
2.	Assam	2.217	15.	Orissa	4.578
3.	Bihar	4.260	16.	Punjab	1.007
4.	Gujarat	9.946	17.	Rajasthan	19.902
5.	Haryana	1.591	18.	Sikkim	0.303
6	Himachal Pradesh	1.914	19.	Tamil Nadu	3.640
7.	Jammu & Kashmir	0.883	20.	Tripura	0.167
8.	Kamataka	10.989	21.	Uttar Pradesh	7.110
9.	Kerala	1.757	22.	West Bengal	1.033
10.	Madhya Pradesh	19.610	23.	Arunachal Pradesh	2.444
11.	Maharashtra	19.181	24.	Goa	0.200
12.	Manipur	0.374	25.	Mizoram	0.421
13.	Meghalaya	0.837	26.	Union Territories	0.349

(Source: Ref. 5)

For purposes of developing appropriate technologies for soil conservation, Central Soil and Water Conservation Institute has considered the erosion problem areas of the country under three categories as hilly regions, ravine regions and semi-arid, black and red soil regions. The characteristic features of these regions are as in Table 10.13(b).

Table 10.13(b) Region-wise Soil Erosion Problems

Region	Area	Extent (M ha)	Sub-areas	Details
Hilly Region	Western, North-Western & Central Himalaya	31.13	J & K, UP (hill Districts) and HP	Area is prone to erosion hazards due to weak geology, deforestation & hill road construction.
	Eastern Himalayan Region	17.70	Assam. Eastern states, Sikkm and West Bengal	Shifting cultivation has caused denudation and degradation of land. Heavy run-off and massive soil erosion.
	Western Ghats	7.74	T.N., Kerala, Karnataka and Maharashtra	Heavy rainfall in the range 1300 to 6000 mm. Prone to severe erosion due to deforestation, faulty land use and overgrazing.
Ravine Region	Arid to Semi arid regions	3.67	Parts of UP., M.P., Bihar, Rajasthan,	Faulty land use, overgrazing and loss of natural land cov-

(*Contd.*)

(*Contd.*)

			Gujarat, Punjab, W.B., I.N. and Maharashtra	ering are the chief causes of gully and ravine formation and soil erosion.
Semi-arid Black and Red Soil Region	Arid to Semi-arid tropical region.	97.00	Rest of the country in semi-arid tropical region not covered in the above	About 500 to 2000 mm of rainfall and 80 to 90% of rainfall received in 30 to 70 hours. Sheet erosion caused by high intensity rainfall.

(Source: Ref. 5)

Reservoir Sedimentation

A large number of reservoirs have been built in India since 1950. Sedimentation in the reservoirs has been found to be fairly high particularly in those reservoirs sited in arid and semi-arid tropical erodible regions. Reservoir surveys conducted during 1958 to 1986 indicated that all of the surveyed reservoirs were found to be silting at a rate faster than what was anticipated. In a majority of the reservoirs about 50% of sediment is deposited in the upper 20–30% of the depth indicating deposition in the head reaches of the reservoir. Reference 7 reports the details of surveys on a large number of reservoirs. A summary of sedimentation surveys on 19 reservoirs covering different regions of the country is given in Table 10.14. It is seen from this Table that the reservoirs are losing annually a capacity of about 0.75 of its original value. Further, the range of loss of reservoir capacity is 1.79 to 0.02% and in majority of cases the actual rate of sedimentation is many times more than the designed rates.

CWC (1991) found from an analysis of capacity survey data of 49 reservoirs in India that there is wide variability in rate of sedimentation in various reservoirs. The sedimentation rate in the surveyed reservoirs was found to lie in the range of 0.15 to 27.85 ha.m/100 sq.km/year.

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10. Central Water Commission, Govt. of India, *"Compendium of Silting of Reservoirs"*, New Delhi, 1991.

Table 10.14 Rate of Silting in Some Reservoirs in India

Sl. No.	Name of Reservoir	River	Storage Capacity (Mm^3)	Catchment Area (km^2)	Year of Impounding	Sedimentation in ha-m/100 km^2/year		Period (years)	Yearly Average Loss in capacity (%)
						Designed rate	Observed rate (Average for period)		
1	Sriramasagar	Godavari	3171.9	91751	1970	3.57	6.19	14	1.79
2	Nizamsagar	Manjira	841.2	21694	1930	2.38	4.89	45	1.26
3	Panchet Hill	Damodar	1581.0	10878	1956	6.67	5.89	29	0.40
4	Maithon	Barakae	1348.8	6294	1955	9.05	10.25	24	0.48
5	Ukai	Tapi	8510.0	62224	1972	1.49	7.16	12	0.53
6	Kadana	Mahi	1543.0	255520	1977	1.30	3.92	7	0.65
7	Pongh	Beas	8579.0	12562	1974	NA	27.85	12	0.41
8	Tungabhadra	Tungabhadra	3751.2	28180	1953	4.29	6.48	32	0.49
9	Bhadar	Bhadar	239.2	2435	1963	7.60	11.61	11	1.18
10	Gandhi Sagar	Chambal	7740.0	23025	1960	3.57	8.96	16	0.29
11	Girna	Girna and Panzam	608.8	4729	1965	0.56	7.49	14	0.58
12	Shivaji Sagar (Koyna)	Koyna	2987.8	891	1961	6.67	7.71	10	0.02
13	Hirakud	Mahanadi	8105.0	83395	1957	2.50	6.62	27	0.61
14	Bhakra	Satluj	9869.0	56980	1958	4.29	5.57	29	0.32
15	Matatila	Betwa	11.3	20720	1956	1.33	6.00	28	1.10
16	Ramganga	Ramganga	2449.6	3134	1975	4.25	22.94	10	1.10
17	Ichari	Tons	11.6	4913	1972	NA	1.33	6	0.65
18	Dhukwan	Betwa	106.5	21340	1907	0.43	0.30	73	0.61
19	Mayurakshi	Mayurakshi	607.7	1860	1955	3.75	16.83	15	0.52

Source: Compendium on Silting of Reservoirs in India, CWC, 1991

Revision Questions

10.1 Describe different forms of land erosion by water.

10.2 Describe the flow-duration and sediment rating curve procedure of estimating the sediment yield of a watershed.

10.3 Explain briefly the Universal Soil Loss Equation (USLE).

10.4 What is Modified Universal Soil Loss Equation (MUSLE)? What is its chief advantage over USLE?

10.5 Briefly explain:
(a) Erosion Index
(b) Sediment Delivery Ratio (SDR)
(c) Bed Load
(d) Suspended Load
(e) Reservoir Delta

10.6 What is meant by Trap Efficiency of a reservoir? What factors influence its value?

10.7 Describe a commonly used method of estimating the trap efficiency of a reservoir.

10.8 Describe the procedure of conducting a Reservoir survey.

10.9 List the factors affecting the density of sediment deposited in a reservoir. What is the commonly used method of estimating the average density of sediment deposited over a period of T years in a reservoir?

10.10 How are reservoirs classified for purposes of estimating the deposition pattern?

10.11 Explain the empirical–area–reduction method of determining the sediment distribution in a reservoir.

10.12 Explain the area–increment method of determining the sediment distribution in a reservoir.

10.13 Explain a procedure to estimate the time taken for a reservoir to lose x% of its initial volume.

10.14 List different methods available for reservoir sediment control.

10.15 Write a brief note on procedures to be adopted towards reduction of sediment yield of a catchment.

Problems

10.1 For a catchment area of 1500 km^2, estimate the sediment yield in ha-m/100 sq. km/year by using (i) Khosla's formula and (ii) Joglekar's formula.

10.2 If the dry unit weight of a sediment deposit in a reservoir is 850 kg/m^3, estimate the (a) porosity and (b) weight of 1 m^3 of sediment deposit in the reservoir. [Assume relative density of sediment particles as 2.65.]

10.3 Estimate the (dry) unit weight of a reservoir sediment deposit having 25% sand, 35% silt and 40% clay, at the end of (a) one year and (b) 25 years. [Assume that normally the reservoir undergoes considerable drawdown.]

10.4 Reservoir sediment deposition survey of a reservoir indicated the following composition of sediment in a sample: Sand = 25%, Silt = 21% and Clay = 54%. The sample can be taken as a 10 year old deposit. If the dry unit weight was 1650 kg/m^3, determine the accuracy of estimate of unit weight of the sample by the use of Koezler equation. The reservoir operation is of 2nd kind viz, normally moderate drawdown is expected in its operation.

10.5 A reservoir sediment is estimated through use of Koezler equation to have average unit weight of 1100 kg/m^3 at the end of 35 years and 1120 kg/m^3 at the end of 50 years. Estimate the average unit weight at the end of first year of deposit and at the end of 100 years.

10.6 In a reservoir the average weight of deposited sediment was found to be (i) 500 kg/m^3 over a period of first ten years, and (ii) 600 kg/m^3 over a period of first twenty years.
Estimate the average unit weight over a period of first 50 years of the reservoir's life.

10.7 A reservoir with a capacity of 50 Mm^3 is proposed at a location in a river having the following properties:
Catchment area = 200 km^2
Average Annual water yield at the site = 35 cm
Average Annual Sediment yield at the site = 150,000 Mm^3
Estimate the time required for the loss of 30% of initial capacity of the reservoir due to sedimentation. [Assume three equal steps of capacity loss.]
The reservoir is expected to be a normal ponded reservoir.

10.8 A reservoir has an initial capacity of 90000 ha-m and the annual sediment load in the stream is estimated as 600 ha-m. If the average annual inflow into the reservoir is 400000 ha-m, estimate the time in years for the reservoir to lose 50% of initial capacity. In the relevant range the trap efficiency η_t can be assumed to be given by

$\eta_t = 6.064\ Ln(C/\mathrm{I}) = 101.48$

Use five steps.

10.9 A proposed reservoir has a catchment of 2660 km^2. It has a capacity of 360 Mm^3 and the annual yield of the catchment is estimated as 40 cm. Assuming the average composition of sediment as 20% sand, 35% silt and 45% clay, estimate the probable life of the reservoir to a point where 40% of the reservoir capacity is lost by sedimentation. The sediment yield is estimated independently as 360 tonnes/km^2/year. [Assume the reservoir to have normally a moderate reservoir drawdown. Take five capacity steps for the life calculation.]

10.10 Coordinates of suspended load rating curve and flow duration curve of a river at a gauging site is given below. Plot the respective curves and using them estimate the (a) total sediment yield at the gauging station and (b) concentration of suspended load in ppm. [Assume bed load as 10% of suspended load.]

Flow Duration Curve		Suspended Sediment Rating Curve	
Percent times flow equalled or exceeded	**Average daily discharge**	**Water discharge (m^3/s)**	**Suspended load (tonnes/day)**
0.5–1.0	2550	2550	355,000
1.5–5.0	1275	1250	200,000
5.0–15.0	735	750	62,500
15.0–35.0	450	450	22,500
35.0–55.0	200	350	17,500
55.0–75.0	110	225	10,000
75.0–95.0	50	125	4000
95.0–99.5	20	85	2000
		50	500
		25	50

10.11 A reservoir has a capacity of 180 Mm^3 at its full reservoir level. The average water inflow and average sediment inflow into the reservoir are estimated as 400 Mm^3/year and 3.00 M tonnes/year respectively. The sediment inflow was found to have a composition of 20% sand, 30% silt and 50% clay. Estimate the time in years required for the capacity of the reservoir to be reduced to 35% of its initial capacity. [Assume the sediment is always submerged.]

10.12 The area of a reservoir at different elevations as obtained by survey is shown in the following table. Estimate the capacity of the reservoir by using the weighted area method. Plot the capacity – elevation above bed curve on log-log axes and estimate the value of parameter m and the reservoir type.

Elevation (m)	Area (ha)	Capacity in (ha.m)
560.52	0	0
562.35	19.42	11.8
563.27	47.75	41.8
563.88	62.32	75.3
564.18	79.72	96.5
564.49	96.72	123.8
565.10	137.59	194.8
565.55	191.41	268.7
566.93	366.64	647.2
568.45	513.95	1313.3
569.97	679.06	2217.1

10.13 Original Reservoir the capacity – area – elevation data of Bhakra reservoir, India, is given below. Estimated total accumulation of sediment in the reservoir in 25 years of its operation is 92250 ha-m. Original bed elevation is E1.350.52 m and the spillway crest is at 512.06 m. Determine the distribution of 92,250 ha-m of sediment in the reservoir by the empirical area reduction method. The reservoir can be taken as of Type II. Assume the level up to which the reservoir is fully covered by sediment at the end of 25 years as 365.76 m. [Use average end area method for computing incremental volume.]

Elevation (m)	Original area (ha)	Original capacity	Elevation (m)	Original area (ha)	Original capacity (ha.m)
350.52	0	0	426.72	4452	148830
365.76	364	2460	441.96	5382	222630
381.00	1295	13530	457.20	6799	317340
396.24	2428	43050	472.44	8620	436650
400.00	2752	55350	487.68	11048	587940
411.48	3561	87330	502.92	13760	772440
			512.06	15378	910200

10.14 For a reservoir the original area – elevation – capacity relation is as given below. Over a period of 10 years, this reservoir expects a total sediment inflow of 10,000 ha-m. Determine the distribution of 10,000 ha-.m of sediment in this reservoir by the area-increment method. [An accuracy of >99.5% in gross sediment volume is expected.]

Elevation (m)	Original area (ha)	Original capacity (ha.m)	Elevation (m)	Original area (ha)	Original capacity (ha.m)
97.53	0	0	112.77	1659	7258
100.58	43.7	98	115.82	2241	13242
103.63	168.4	471	118.88	3083	21300
105.76	411.2	1177	121.92	4346	32550
106.68	464.2	1509	124.97	6206	42710
109.73	720.7	3321			

Objective Questions

10.1 In a reservoir the capacity is 20 cm and the annual inflow is estimated to be 25 cm. The trap efficiency of this reservoir under normal operating conditions is about
(a) 10% (b) 45% (c) 75% (d) 100%

10.2 In a reservoir the sediment deposit is found to be made up of only sand and this deposit is always found to be submerged. The unit weight of this sediment deposit at any time *T* years after the commencement of operation of the reservoir is about
(a) 1500 kg/m^3
(b) 1500 + $B \, Ln \, T$ kg/m^3 where *B* is a positive non-zero coefficient
(c) 750 kg/m^3
(d) 750 + $B \, Ln \, T$ kg/m^3 where *B* is a positive non-zero coefficient

10.3 Borland & Miller's classification of reservoirs for distribution of sediments in the reservoir is based on a parameter *m*. The reservoir is classified as
(a) Type I if *m* is in the range 2.5 to 3.5 (b) Type II if *m* is in the range 1.0 to 1.5
(c) Type III if *m* is in the range 1.5 to 2.5 (d) Type IV if *m* is greater than 3.5

10.4 A reservoir had an original capacity of 720 ha-m. The drainage area of the reservoir is 100 sq.km and has a sediment delivery rate of 0.10 ha-m/sq.km. If the reservoir has a trap efficiency of 80% the annual percentage loss of original capacity is
(a) 1.39% (b) 1.11% (c) 1.74% (d) 0.28%

10.5 The sediment delivery ratio (SDR) of a watershed is related to watershed area (*A*), relief (*R*) and watershed length (*L*) as
(a) $SDR = KA^m (R/L)^n$ (b) $SDR = KA^{-m} (R/L)^{-n}$
(c) $SDR = KA^{-m} (R/L)^n$ (d) $SDR = KA^m (R/L)^{-n}$
where *K*, *m* and *n* are positive coefficients.

10.6 If erosion in a watershed is estimated as 30 tonnes/ha/year, his watershed is in erosion class designated as
(a) severe (b) very high (c) high (d) moderate

10.7 The suspended sediment concentration C_s in ppm is determined from a sample of suspended sediment mixture as

(a) $$C_s = \frac{[\text{Weight of sediment in sample}]}{[\text{Weight of water in sample}]} \times 10^6$$

(b) $$C_s = \frac{[\text{Weight of sediment in sample}]}{[\text{Weight of (sediment + water) in sample}]} \times 10^6$$

(c) $$C_s = \frac{[\text{Volume of sediment in sample}]}{[\text{Volume of (sediment + water) in sample}]} \times 10^6$$

(d) $$C_s = \frac{[\text{Weight of (sediment + water) in sample}]}{[\text{Volume of (sediment + water) in sample}]} \times 10^6$$

10.8 The current CWC practice in design of reservoirs adopts minimum drawdown level (MDDL) based on the bed elevation that will be reached in the reservoir after *N* years of sedimentation, where *N* is equal to
(a) 25 years (b) 50 years (c) 100 years (d) 500 years

10.9 The present CWC practice in design of reservoirs adopts area – capacity – elevation curves expected after *M* years of sedimentation for working table studies and checking for the performance of the project. In this *M* is equal to
(a) 25 years (b) 50 years (c) 100 years (d) 500 years

Appendix A

Additional References, Some Useful Websites, Abbreviations

A.1 ADDITIONAL REFERENCES

1. Bedient, P.B. and Huber, W.C., *Hydrology and flood plain analysis,* Addison-Wesley Pub. Co., 1988.
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4. Gurmeet Singh et al., *Manual of Soil and Water Conservation Practices*, Oxford & IBH Pub. Co., New Delhi, 1990.
5. Karanth, K.R., *Hydrogeology,* Tata McGraw-Hill Pub. Co., New Delhi, India, 1989.
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9. Singh, V.P., *Elementary Hydrology*, Prentice-Hall, 1992.
10. Viessman, W. et al., *Introduction to Hydrology*, 3rd ed., Harper & Row, New York, 1989.

A.2 SOME USEUL WEBSITES RELATED TO HYDROLOGY (AS OF 2007)

1. U.S. Geological Survey www.usgs.gov
2. Hydrology Web http://hydrologyweb.pnl.gov
3. Kumar Link to Hydrology Resources
   www.angelfire.com/nh/cpkumar/hydrology.html
4. WRCS Hydraulic & Hydrology Software shop
   http://www.waterengr.com
5. New Mexico University – Earth & Environmental Science – Useful Links
   http://www.ees.nmt.edu

6. Yahoo Search
   http://dir.yahoo.com/Science/Engineering/Civil_Engineering
7. Internet Resources for Water
   http://www.library.ucsb.edu/istl/97-summer/internet1.html
8. Links to Interesting Water Resource web pages
   http://www.uswaternews.com
9. Water Meta Pages
   http://www.interleaves.org/~rteeter/watermeta.html
10. Directory of Hydrology related WWW sites
    http://hydrology.agu.org/news/resources.html

A.3 ABBREVIATIONS

AET	Actual Evapotranspiration
AI	Aridity index
AMC	Antecedent moisture condition
CBIP	Central Board of Irrigation & Power (India)
CGWB	Central Groundwater Board (India)
CN	Curve number
CWC	Central Water Commission (India)
DAD	Maximum Depth – Area – Duration
DGPS	Differential Global Positioning System
DRH	Direct runoff hydrograph
DVC	Damodar Valley Corporation
El_{30}	Rainfall Erosion Index Unit
ER	Effective (or Excess) rainfall
ERH	Effective (or Excess) rainfall hyetograph
FAO	Food & Agriculture Organisation of United Nations Organisation.
FEM	Finite Element Method
FRL	Full Reservoir Level
GOI	Government of India
GPS	Geographical Positioning System
IMD	India Meteorological Department
IUH	Instantaneous Unit Hydrograph
MAI	Moisture availability index
MCM	Million Cubic Metre
MDDL	Minimum Drawdown Level
MOC	Method of Characteristics
MSL	Mean Sea Level
MUSLE	Modified Universal Soil Loss Equation
NBSS&LUP	National Bureau of Soil Survey & Land Use Planning
NCIWRD	National Commission for Integrated Water Resources Development (1999)
NRSA	National Remote Sensing Agency
PET	Potential evapotranspiration

PI	Palmer Index
PMF	Probable maximum flood
PMP	Probable maximum precipitation
RBA	Rashtriya Barh Ayog (National Flood Commission)
RTWH	Roof Top Water Harvesting
SCS	U.S. Soil Conservation Service
SDR	Sediment Delivery Ratio
SPF	Standard Project Flood
SPS	Standard Project Storm
SRK	Standard Runga-Kutta Method
SWM	Stanford Watershed Model
TMC	Thousand Million Cubic Feet
UH	Unit hydrograph
UNESCO	United Nations Economic, Social & Cultural Organisation
USLE	Universal Soil Loss Equation
WMO	World Meteorological Organisation

Appendix B

CONVERSION FACTORS

B.1 VOLUME

1 m^3 = 35.31 cubic feet = 264 US gallons = 220 Imp. gallons
= 1.31 cubic yards = 8.11 × 10^{-4} acre feet = 1000 litres

B.2 FLOW RATE (DISCHARGE)

Unit	Cubic metres per second (m^3/s)	Litres per minute (lpm)	Litres per second (lps)
1 cft/s (cusec)	0.02832	1699	28.32
1 Imp. gpm	7.577 × 10^{-5}	4.546	0.07577
1 US gpm	6.309 × 10^{-5}	3.785	0.06309
1 Imp. mgd	0.05262	3157	52.62
1 acre ft/day	0.01428	856.6	14.28

B.3 PERMEABILITY

1. *Specific permeability, K_0*
   1 darcy = 9.87 × 10^{-13} m^2 = 9.87 × 10^{-9} cm^2
2. *Coefficient of permeability, K*
   1 lpd/m^2 = 1.1574 × 10^{-6} cm/s
   1 m/day = 1.1574 × 10^{-3} cm/s = 20.44 Imp. gpd/ft^2 = 24.53 US gpd/ft^2
   = 0.017 US gpm/ft^2

B.4 TRANSMISSIBILITY

1 m^2/day = 67.05 Imp. gpd/ft = 80.52 US gpd/ft = 0.056 US gpm/ft

EQUIVALENTS OF SOME COMMONLY USED UNITS

1 Metre	**=**	**3.28 feet**	**1 Foot**	**=**	**30.48 cm = 0.3048 m**
1 Kilometre	**=**	**0.6215 mile**	**1 Mile**	**=**	**1.609 km**
1 Hectare	**=**	**2.47 acres**	**1 Acre**	**=**	**0.405 ha**
1 sq. km	**=**	**100 ha**	**1 Sq. Mile**	**=**	**259 ha = 640 acres**
1 Million Cubic metre (MCM)	**=**	**810.71 Acre ft. = 0.0353 TMC**	**1 TMC = one thousand million cubic feet**	**=**	**28.317 million cubic metres (MCM)**
			1 Million acre feet	**=**	**1233.48 million cubic feet**
			1 cusec. day	**=**	**86400 cft = 2446.9 m^3**
			1 million gallons (imperial)	**=**	**160544 Cubic feet = 4546.09 Cubic metres**

Answers to Objective Questions

Chapter	0	1	2	3	4	5	6	7	8	9
1.00		c	d	a	b	c	d	c	a	c
2.00		d	b	c	d	c	a	b	b	c
2.10	c	d	a	d	c	b	b	d	b	b
2.20	b	a	a	b	c	a	b			
3.00		c	b	d	c	c	d	b	d	c
3.10	c	b	b	b	c	d	b	d	c	
4.00		d	d	b	d	c	b	a	c	d
4.10	b	a	c	b	a	b	c	b	c	c
5.00		a	a	b	a	c	c	b	c	b
5.10	d	c	b	a	b	c	b	c	a	
6.00		c	a	b	a	c	b	b	b	b
6.10	c	b	d	c	a	d	a	d	b	d
6.20	b	a	b	c	b					
7.00		a	d	a	c	c	b	b	d	a
7.10	a	c	c	c	a	c	a	c	c	b
7.20	d									
8.00		a	b	a	d	c	b	d	d	c
8.10	d	b	a	b	a	b	b	c	d	c
8.20	d	a								
9.00		d	b	b	c	c	d	b	c	a
9.10	b	c	c	b	d	d	d	a	c	a
9.20	d	a	a	b	b	a	b	d	b	
10.00		d	a	c	b	c	b	b	c	b

ANSWERS TO PROBLEMS

CHAPTER 1

1.1 $Q = 57.87\ m^3/s$

1.2 (i) 0.61 (ii) Increase in abstraction = 18.492 Mm^3

1.3 $Q = 6.191\ m^3/s$ **1.4** $S_2 = 19.388$ ha.m

1.5 $\bar{P} = 1105$ mm, $\bar{E} = 532.4$ mm, $r_a = 0.485$, $r_b = 0.472$, $r_c = 0.522$, $r_d = 0.538$, $r_{total} = 0.518$

1.6 (i) $T_r = 8.2$ days (ii) $T_r = 4800$ years (iii) $T_r = 28{,}500$ years

CHAPTER 2

2.1 5 **2.2** 12.86 cm

2.3 (a) 1955 (b) Correction ratio = 0.805, mean $P_A = 143.9$ cm

2.4

Time since start of the storm (minutes)	30	60	90	120	150	180	210
Intensity of rainfall in the interval (cm/h)	3.50	4.50	12.0	9.0	5.0	3.0	1.5
Cumulative rainfall since start (cm)	1.75	4.00	10.00	14.50	17.00	18.50	19.25

Average intensity = 5.5 cm/h

2.5 36.06 mm **2.6** Years 1964, 1971, 1972, 1976 and 1980 were drought years.

2.7 7.41 cm **2.8** 135 cm

2.9 (a) 10.6 cm (b) 10.80 cm (c) 11.07 cm

2.10 112.03 cm

2.11 (i) Average depth = 20.1 mm (ii) Depth at storm centre = 22.0 mm.

2.12 (a)

Time (min)	0	10	20	30	40	50	60	70	80	90
Intensity (mm/h)		114	132	42	120	138	198	168	48	36

(b)

Duration (min)	10	20	30	40	50	60	70	80	90
Max. Intensity (mm/h)	198	183	168	156	134.4	133	130.3	120	110.7

2.13

Duration (min)	10	20	30	40	50	60	70	80	90
Max. Depth (mm)	16	25	31	40	47	55	60	64	67

2.14

Maximum Intensity	75.0	62.1	49.8	40.5	37.0	33.0	30.1	27.2	24.7
Duration in Min	10	20	30	40	50	60	70	80	90
Maximum Depth (mm)	12.5	20.7	24.9	27.0	30.9	33.0	35.1	36.2	37.0

2.15 (a) 132.50 cm (b) 143.0 cm
2.16 (a) 118.0 cm (b) $T = 3.5$ years (c) $p_{66.7} = 88.0$ cm; $p_{75} = 84.5$ cm
2.18 (a) 0.167 (b) 0.0153 (c) 0.183
2.19 (a) 0.605 (b) 0.01
2.20 10 years **2.21** (a) 0.155 (b) 0.00179 (c) 0.0845

Chapter 3

3.1 10.7 mm/day **3.2** 24.5 mm **3.3** Decrease, 48 Mm^3
3.4 175 mm/month **3.5** (a) 27.1 cm (b) 32.28 cm
3.6 23.4 cm **3.7** 46.8 cm **3.8** 11.25 cm/month
3.9 3.9 mm/day for Day 2 and Day 7; 3.6 mm/day on Day 9
3.10 $f_p = 1.0 + 10.45e^{-3.1t}$
3.11 $K_h = 4.1235\ h^{-1}, f_c = 3.21$ cm/h, $f_o = 41.278$ cm/h
3.12 Kostiakov: $F_p = 6.733t^{0.7393}$

Green – Ampt: $f_p = 9.0239\left(\frac{1}{F_p}\right) + 3.8375$

Philip: $f_p = 2.9735t^{-0.5} + 2.0461$

3.13 $K_h = 3.06\ h^{-1}, f_c = 1.50$ cm/h, $f_o = 27.935$ cm/h
3.14 Kostiakov: $F_p = 4.245\ t^{0.7841}$

Philip: $f_p = 1.911\ t^{-0.5} + 1.485$

Green – Ampt: $f_p = 3.9785\left(\frac{1}{F_p}\right) + 2.305$

3.15 (a) (i) $f_p = 0.7598\ t^{-1.185}$
(ii) $F_p = 7.4827 \ln t + 34.781$
(b) $K_h = 1.91\ h^{-1}$, $f_c = 0.10$ cm/h, $f_o = 10.244$ cm/h
3.16 $f_{av} = 1.02$ cm/h
3.17 (i) At $t = 2.0$ h $f_p = 1.7$ cm/h
(ii) At $t = 3.0$ h $f_p = 1.51$ cm/h
3.18 φ-index = 0.42 cm/h **3.19** φ-index = 0.657 cm/h, $t_e = 3.5$ hours
3.20 W-index = 2.52 mm/h **3.21** R = 2.50 cm **3.22** R = 2.24 cm

Chapter 4

4.1 6.426 m^3/s

4.2 (i) $\frac{\bar{v}}{v_{0.6}} = \frac{1}{(0.4)^m\ (m+1)}$ (ii) (a) $\frac{\bar{v}}{v_{0.6}} = 1.001$ (b) $\frac{\bar{v}}{v_{0.6}} = 1.00036$

4.3 11.895 m^3/s **4.4** 3458.9 m^3/s **4.5** 103 m^3/s **4.6** 500 m^3/s
4.7 142.8 m^3/s **4.8** 11 km **4.9** 44.25 m^3/s **4.10** 30.18 m^3/s
4.11 (1) $Q = 159.44\ (G - a)^{1.371}$, (2) 0.968 (3) 2525 m^3/s, 5368 m^3/s
4.12 426.9 m^3/s **4.13** $a = 18.60$ m
4.14 $(G - 20.5) = 0.1641\ Q^{0.4648}$, Stage = 26.842 m **4.15** 164.4 m^3/s

Chapter 5

5.1 (a) 121 cm (b) 62.7%
5.2 $R = 0.4828\ P - 0.2535$; 5.06 Mm^3 **5.3** $R = 0.6163\ P - 21.513$; 40.12 cm
5.4 10143 Mm^3; 12842 Mm^3 **5.5** 0.144

5.6

Month	July	August	September	October
Monthly Yield (m^3)	41580	430290	177120	751410
Total seasonal yield (Mm^3)		1.44		

5.7 (a) 59550 m^3 (b) 180800 m^3
5.8 $CN_I = 51.4$, $CN_{II} = 70.7$, $CN_{III} = 85.0$
5.9 346080 m^3 **5.10** 620500 m^3 **5.11** 90984 m^3
5.12 140.15 mm **5.13** (a) 122.4 mm, (b) 105.2 mm; 16%
5.14 $Q_{75} = 14\ m^3/s$ **5.15** 9545 cumec.day
5.16 (a) 5700 cumec.day; (b) 82 m^3/s **5.17** 365 Mm^3
5.18 389.12 Mm^3 **5.19** 91.032 ha.m **5.20** 389.12 Mm^3
5.21 16.74 Mm^3; 1.41 Mm^3/day; Nil **5.22** 27 Mm^3 less water

Chapter 6

6.1 $K_{rh} = 0.886$, $K_{rs} = 0.2217$, $S_{t7} = 9.12$ cumec.day
6.2 (a) $K_{rb} = 0.966$ (b) $Q_3 = 28.28\ m^3/s$ **6.4** 2.47 Mm^3

Time (h)	1	2	3	4
Average ER (min)	1.44	25.50	3.94	0

6.5 (Given ordinates/4.32)
6.6 Base = 66 hour; $q_p = 15.91\ m^3/s$ at 10 hours from start

6.7

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72
6-h UH ord. (m^3/s)	0	5.0	35.0	64.0	72.0	62.0	45.8	32.8	20.8	11.6	5.6	1.6	0

6.8 ER = 5.76 cm

Time (days)	0	1	2	3	4	5	6	7	8
1-day Dist. graph (%)	0	10.50	31.50	26.25	15.50	9.25	5.25	2.00	0

6.9 Ordinates of 8-h UH = (Given ordinates/4.5) **6.10** 70 m^3/s
6.11 Volume of Direct Surface runoff = 5.78 Mm^3
Peak runoff rate = 1376 m^3/s

6.12

Time (h)	0	3	6	9	12	18	24	30
$Q(m^3/s)$	30	300	480	1410	2060	4450	6010	6010
Time (h)	36	42	48	54	60	66	72	78
$Q(m^3/s)$	5080	3996	2866	1866	1060	500	170	30

6.13

Time (h)	0	6	12	18	24	30	36	42
Q(m^3/s)	10	30	90	220	280	220	166	126
Time (h)	48	54	60	66	72			
Q(m^3/s)	92	62	40	20	10			

6.14

Time (h)	0	6	12	18	24	30	36	42
12-h UH ord. (m^3/s)	0	10	40	105	135	105	78	58
Time (h)	48	54	60	66	72			
12-h UH ord. (m^3/s)	41	26	15	5	0			

6.15

Time (h)	0	2	4	6	8	10	12	14
S-curve ord. (m^3/s)	0	25	125	285	475	645	755	825
4-h UH ord. (m^3/s)	0	12.5	62.5	130	175	180	140	90
Time (h)	16	18	20	22	24	26		
S-curve ord. (m^3/s)	855	875	881	881	881	881		
4-h UH ord. (m^3/s)	50	25	13	3	0	0		

6.16 160 m^3/s

6.17 Area = 7.92 km^2

Time (h)	0	1	2	3	4	5	6	7
S-curve ord. (m^3/s)	0	5	13	18	21	22	22	22
2-h UH ord. (m^3/s)	0	2.5	6.5	6.5	4.0	2.0	0.5	0

6.18

Time (h)	0	6	12	18	24	30	36	42	48	54
6-h UH ord. (m^3/s)	0	20	54	98	124	148	152	154	138	122
Time (h)	60	66	72	78	84	90	96	102	108	114
6-h UH ord. (m^3/s)	106	92	76	66	50	42	28	22	12	10
Time (h)	120	126	132	138						
6-h UH ord. (m^3/s)	6	3	1	0						

6.19

Time (h)	0	3	6	9	12	15	18	21	24	27	30	33
9-h UH ord. (m^3/s)	0	4	29	73	129	174	191	183	158	135	115	99
Time (h)	36	39	42	45	48	51	54	57	60	63	66	
9-h UH ord. (m^3/s)	83	69	54	43	33	25	18	12	6	2	0	

6.20

Time (h)	0	6	12	18	24	30	36	42
Q (m^3/s)	20	80	200	550	620	890	698	530
Time (h)	48	54	60	66	72	78		
Q (m^3/s)	380	280	178	100	60	20		

6.21 A = 1296 km^2

Time (h)	0	6	12	18	24	30	36	42
Q (m^3/s)	25	75	225	375	525	600	525	450
Time (h)	48	54	60	66	72	78		
Q (m^3/s)	375	300	225	150	75	25		

6.22 80.5 m^3/s

6.23

Time (h)	0	2	6	10	14	18	22	26	30	34
DRH ord. (m^3/s)	0	4.3	19.4	44.4	39.6	28.1	14.1	4.9	1.4	0

6.24

Time (Units of 6 h)	1	2	3	4	5	6	7	8
Dist. Graph ord. (%)	6.25	18.75	22.92	18.75	14.58	10.42	6.25	2.08

6.25 91.4% and 59.44%

6.26

Time (h)	0	3	6	9	12	15	18	21	24	27
3-h UH ord. (m^3/s)	0	60	120	90	50	30	20	10	5	0

6.27 $t_R = 6.0\ h$; $t'_p = 27.75\ h$; $Q_p = 126\ m^3/s$; $W_{50} = 79\ h$; $W_{75} = 45\ h$; $T_b = 156\ h$

6.28 $t'_p = 9\ h$; $Q_p = 86.5\ m^3/s$; $W_{50} = 30.7\ h$, $W_{75} = 17.5\ h$; $T_b = 52\ h$

6.29 $Q_p = 126\ m^3/s$, $T_p = 30.75$ h and to be used with Table 6.12 in the Text.

6.30

Time (h)	0	1	2	3	4	5	6	7	8
Ordinate of 4-h UH (cm/h)	0	1	2	3	4	3	2	1	0
Ordinate of S_4-curve (cm/h)	0	1	2	3	4	4	4	4	4
Ordinate of 3-h UH (cm/h)	0	1.33	2.67	4.0	4.0	2.67	1.33	0	

6.31

Time (h)	0	1	2	3	4	5	6	7	8
Ordinate of S_2-curve (cm/h)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Ordinate of 4-h UH (cm/h)	0.25	0.25	0.25	0.25					

6.32

Time (h)	0	1	2	3	4	5	>5
Ordinate of DRH (m^3/s)	300	300	300	300	300	300	0

6.33 $Q_p = 20.48\ m^3/s$, $T_p = 1.025$ h, $T_b = 2.75$ h
DRH: A triangle with peak of 81.92 m^3/s occurring at 1.025 h from start. Base = 2.75 h

6.34

Time (h)	Ord. of 2-h UH (m^3/s)	Time (h)	Ord. of 2-h UH (m^3/s)
0	0.00	8	17.50
2	2.50	10	19.29
4	7.50	12	17.8
6	12.50	14	16.4
16	15.00	28	6.43
18	13.57	30	5.00
20	12.14	32	3.57
22	10.71	34	2.14
24	69.29	36	0.71
26	37.86	38	0.00

6.35 Area = 257.8 km^2

Time (h)	Ord. of 3-h UH (m^3/s)	Time (h)	Ord. of 3-h UH (m^3/s)
0	0.0	12	42.3
1	1.8	13	36.0
2	9.8	14	30.0
3	26.0	15	24.3
4	46.0	16	19.0
5	62.3	17	14.5
6	70.7	18	10.8
7	71.8	19	7.5
8	68.5	20	4.5
9	62.8	21	2.0
10	56.0	22	0.5
11	49.0	23	0.0

Chapter 7

7.1 4.0 m^3/s **7.2** 10.0 m^3/s **7.3** 19.65 m^3/s **7.4** Q_p = 55.08 m^3/s

7.5 q_m = 311.88 m^3/s occurs at the end of 5 hours after the commencement of the storm

7.6 Q_p = 2.08 m^3/s **7.7** Q_p = 6.42 m^3/s

7.8 See Fig. AnsP–7.8 **7.9** Q_p = 0.345 m^3/s

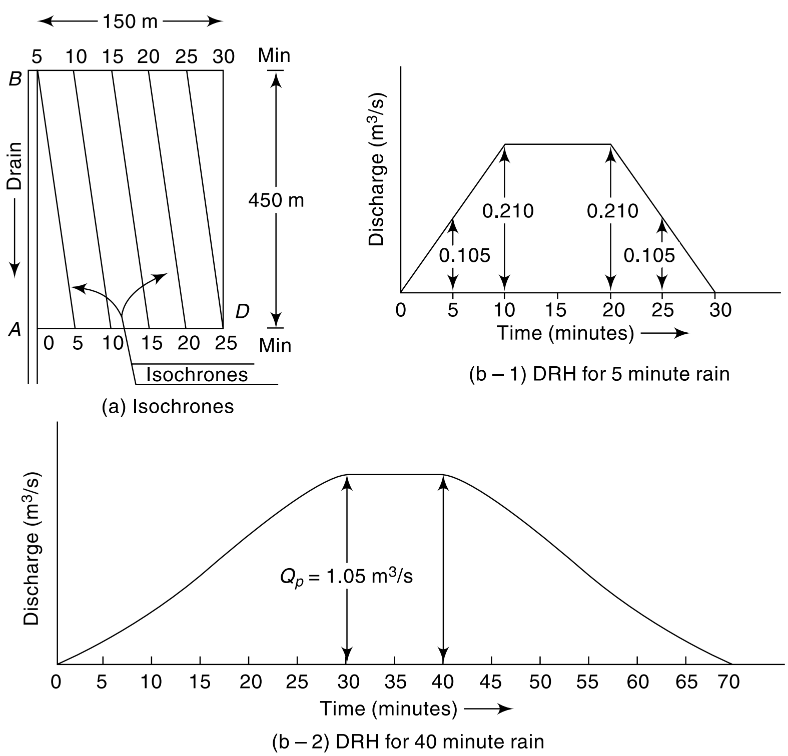

Fig. AnsP–7.8 Answers to Problem 7.8

7.10 (a) 0.025 (b) 0.397 (c) 0.975
7.11 (a) 0.41 (b) 0.358 (c) 0.02
(d) 0.000833 (e) 0.636

7.12

N	35	45	55	60	65
K(T, N)	5.6421	5.5221	5.4420	5.4100	5.3832

7.13

Q_T m^3/s for T =	50	100	1000
Gumbel	5763	6392	8471
Log Pearson-III	5296	5823	7588
Log Normal	5334	5880	7730

7.14 100 years **7.15** 85 years **7.16** 100 years

7.17

Q_T m^3/s for T =	50	100	200	1000
Log Pearson-III	794	928	1077	1496
Log Normal	696	771	846	1025

7.18 22950 m^3/s **7.19** (i) 7896 m^3/s, (ii) 8103 m^3/s
7.20 Ganga: $Q_{100} = 16359 \pm 2554$ m^3/s $Q_{1000} = 22023 \pm 3744$ m^3/s
Yamuna: $Q_{100} = 17298 \pm 3885$ m^3/s $Q_{1000} = 23935 \pm 5721$ m^3/s
7.21 567 m^3/s **7.22** (a) $\bar{x}$ = 385 m^3/s; σ_{n-1} = 223 m^3/s (b) 1525 m^3/s

7.23

Time (h)	0	12	24	36	48	60	72	84
Q (m^3/s)	50	104	482	1669	3139	3699	3358	2603
Time (h)	96	108	120	132	144	156	168	
Q (m^3/s)	1928	1268	753	393	183	51	50	

7.24 Design Storm

Time (h)	0	6	12	18	24
Design strom rainfall excess (cm)	0	2.0	4.4	6.4	2.4

Flood Hydrograph

Time (h)	0	6	12	18	24	30	36
Q (m^3/s)	20.0	45.0	125	285	475	620	666
Time (h)	42	48	54	60	66	72	78
Q (m^3/s)	568	416	264	132	46	20	20

7.25 T = 390 years, $\bar{R}$ = 12% **7.26** R_e = 0.603
7.27 (a) T_a = 10 years (b) T_b = 190 years **7.29** 4908 m^3/s
7.30 T = 247 years; $x_t = C_{hf}$ = 26700 m^3/s; C_{af} = 34,710 m^3/s; Safety margin = 8010 m^3/s

Chapter 8

8.1

Time (h)	0	3	6	9	12	15	18	21	24	27
Q (m^3/s)	0	1	10	27.6	38.29	41.88	40.26	35.35	29.30	23.27
Elevation (300.0 +) m	0.0	0.30	0.45	0.95	1.17	1.24	1.21	1.11	0.99	0.87

8.2

Time (h)	0	3	6	9	12	15	18	21	24	27
Q (m^3/s)	60.84	39.41	38.25	45.86	50.92	49.53	43.81	39.91	32.17	25.08
Elevation (300.00 +) m	1.50	1.19	1.17	1.29	1.36	1.34	1.26	1.20	1.04	0.90

8.3 62.38 m, 55.21 m^3/s, 4.8 m^3/s **8.4** 2 h 25 min

8.5

Time (h)	0	2	4	6	8	10	12	14
Q (m^3/s)	0	6.67	17.78	27.41	28.86	24.38	21.87	18.71
Elev. (200.0 +) (m)	0	0.67	1.78	2.74	2.89	2.44	2.19	1.87
Time (h)	16	18	20	22	24	26		
Q (m^3/s)	15.76	12.75	9.75	6.75	3.75	075		
Elev. (200.0 +) (m)	1.58	1.27	0.98	0.67	0.38	0.07		

8.6

Time (h)	0	2	4	6	8	10	12	14	16
Q (m^3/s)	0	4.0	18.4	43.04	61.82	65.09	59.06	49.43	39.66
Time (h)	18	20	22	24	26	28	30	32	
Q (m^3/s)	29.80	19.88	1193	7.16	4.29	2.58	1.55	0.93	

8.7 K= 10.0 h; x = 0.3 **8.8** 21 h, 35 m^3/s

8.9

Time (h)	0	6	12	18	24	30
Q (m^3/s)	35.00	29.94	25.49	28.91	41.14	69.49

8.10

Time (h)	0	4	8	12	16	20	24	28
Q (m^3/s)	8	8	12	21	25.5	25.25	22.63	18.81

8.11

Time (h)	0	3	6	9	12	15	18	21
Q (m^3/s)	10	13.91	24.63	35.48	41.55	44.08	43.99	41.97
Time (h)	24	27	30					
Q (m^3/s)	38.53	34.02	28.73					

8.12

Time (h)	0	1	2	3	4	5	6	7
IUH Ord. (m^3/s)	0	2.78	13.07	17.32	28.10	34.18	33.55	30.75
1-h UH ord. (m^3/s)	0	1.39	7.92	15.19	22.71	31.14	33.86	32.15
Time (h)	8	9	10	11	12	13	14	
IUH Ord. (m^3/s)	27.67	24.90	22.41	20.17	18.16	16.34	14.71	so on
I-h UH ord. (m^3/s)	29.21	26.29	23.66	21.29	19.16	17.25	15.52	so on

8.13 3 h, 0.6 m^3/s **8.14** $Q = \beta t - \left(\frac{\beta}{\alpha} - I_0\right) e^{-\alpha t} - \frac{\beta}{\alpha}$

8.15

Time (h) (h)	$u(t)$ in (cm/h)	$u(t)$ (m^3/s)	Time (h)	$u(t)$ (cm/h)	$u(t)$ (m^3/s)
0	0	0	33	0.01889	26.25
3	0.00211	2.93	36	0.01487	20.67

(*Contd.*)

(*Contd.*)

6	0.01022	14.20	39	0.01147	15.94
9	0.02092	29.08	42	0.00869	12.08
12	0.03007	41.08	45	0.00648	9.01
15	0.03563	49.52	48	0.00477	6.63
18	0.03734	51.90	51	0.00347	4.82
21	0.03596	49.99	54	0.00250	3.47
24	0.03256	45.26	57	0.00178	2.48
27	0.02812	39.09	60	0.00126	1.75
30	0.02340	32.52	63	0.00089	1.23

8.17

Time (h)	IUH $u(t)$ (m^3/s)	1-h UH (m^3/s)	Time (h)	IUH $u(t)$ (m^3/s)	1-h UH (m^3/s)
0	0	0	10	24.6	29.78
1	25.4	12.68	11	17.0	20.80
2	69.1	47.25	12	11.5	14.22
3	97.2	83.17	13	7.6	9.55
4	104.3	100.73	14	5.0	6.32
5	96.4	100.32	15	3.2	4.13
6	81.1	88.75	16	2.1	2.67
7	64.0	72.56	17	1.3	1.71
8	48.1	56.07	18	0.8	1.08
9	34.9	41.54	20	0.525	0.68

8.18

Time (h)	$u(t)$ in (m^3/s)	Time (h)	$u(t)$ in m^3/s
0	0.000	22	6.062
2	2.242	24	4.571
4	7.692	26	3.386
6	12.857	28	2.472
8	16.008	30	1.782
10	16.962	32	1.270
12	16.228	34	0.896
14	14.471	36	0.627
16	12.255	38	0.435
18	9.978	40	0.300
20	7.876	42	0.206

8.19 $n = 4.18$, $K = 3.35$ h

Chapter 9

9.1 $S = 16.34\%$, RD of solids = 2.517

9.2 (a) 4125 m^3/day (b) 44.175 m **9.3** 1.92 cm/s

9.4 (a) 3.816×10^{-3} (b) –1.12% **9.5** 156.459 m

9.6 31.46 m/day **9.7** 1.73 m **9.8** 4.6 years

9.9 3.2 m^3/day/m length

9.11 (i) $R = 6 \times 10^{-4}$ m^3/day/m width (ii) $h_m = 5.196$ m
(iii) $q_o = -0.06$ m^3/day/m width (iv) $q_1 = 0.18$ m^3/day/m width

9.12 a = 1978.4 m, q_a = –1.0842 m^3/day/m width, q_b = 1.108 m^3/day/m width
9.13 2532 lpm **9.14** 1716 lpm;
(a) 9.5% increase (b) 100% increase (c) 50% inrease
9.15 11.17 m/day **9.17** 2556 lpm, 10.54 m
9.18 K = 25.8 m/day; T = 645 m^2/day, s_w = 10.78 m
9.19 h_A = 10.784 m, h_B = 10.853 m; $(\mathbf{Re})_{PW}$ = 2.653, $(\mathbf{Re})_A$ = 0.0148, $(\mathbf{Re})_B$ = 0.00917
9.20 (a) 1159 lpm (b) 570 lpm **9.21** 7.78 m/day
9.22 2303 m/day **9.23** 1512 lpm **9.24** (a) 17.80 m
(b) T = 136.5 m^2/day (c) 29.33 m (d) 65.2 m and 86.1 m
9.25 (i) 0.943 h^{-1} (ii) 46.3 m^3/h
9.26 (i) 0.3066 h^{-1} (ii) 5.96 m^3/h
9.27 36.0 m^3/h **9.28** T = 105 m^2/day; $S = 1.976 \times 10^{-4}$
9.29 Q = 1611 lpm **9.30** (i) s = 3.3 m, (ii) s = 4.3 m
9.31 1.234 m **9.32** $S = 4.06 \times 10^{-4}$; T = 36.87 m^2/h **9.33** T = 28.1 m^2/h

Chapter 10

10.1 (i) 4.17 ha-m/100 sq. km/year (ii) 10.32 ha-m/100 sq. km/year
10.2 p = 0.679, W = 1529 kg
10.3 W_{T1} = 1199.65 kg/m^3, W_{T25} = 1261.2 kg/m^3 **10.4** 7% under prediction
10.5 1160 kg/m^3 **10.6** 730 kg/m^3 **10.7** 102 years.
10.8 83 years. **10.9** 196 years
10.10 (a) 9.75 M. Tonnes/year; (b) 875 ppm
10.11 T_{35} = 22 years **10.12** m = 3.2

10.13

Sl. No.	Elevation (m)	Final Reservoir Area (ha)	Final Reservoir Capacity (ha.m)
1	350.52	0.0	0
2	365.76	0.0	0
3	381.00	777.3	4351
4	396.24	1807.9	25201
5	400.00	2112.0	35132
6	411.48	2871.5	59481
7	426.72	3720.0	110148
8	441.96	4632.7	172661
9	457.20	6059.1	256023
10	472.44	7921.4	364372
11	487.68	10435.7	505672
12	502.92	13325.1	682193
13	512.06	15378.0	817966

10.14

Elevation (m)	106.68	109.73	112.77	115.82	118.88	121.92	124.97
Reservoir Area after 10 years (ha)	0	256.65	1194.8	1176.8	2618.8	3881.8	5741.8
Capacity after 10 years (ha.m)	0	396	2922	7490	14128	23967	32711

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