Chapter 12

Reservoir Sedimentation

The objectives of this chapter are:

- to explain the problem of reservoir sedimentation and its consequences,
- to explain methods and models of estimation of sediment yield of watersheds,
- to explain the conventional and advanced techniques of reservoir surveys, and
- to explain methods of managing reservoir sedimentation.

Soil erosion is the detachment and transportation of the soil. It is a universal and natural phenomenon. The most important agents that cause soil erosion are precipitation, runoff, wind, and activities of living beings. The eroded soil is carried into water courses by flood and storm waters resulting in tremendous sediment movement. Every stream carries some sediments in suspension and moves larger particles as bed load down to reservoirs, lakes, estuaries, bays, and oceans. The impact of sediment erosion, transport and deposition is widespread.

Uncontrolled deforestation, forest fires, grazing, improper method of tillage, and unwise agricultural and land use practices accelerate soil erosion resulting in a large increase of sediment inflow into streams. The deposition of sediment in channels or reservoirs creates a variety of problems, such as raising of stream beds, increasing flood heights, choking of navigation channels and, of course, depletion of capacity in storage reservoirs.

The sediment content in rivers varies from month to month. While it is negligible in winter and summer months, it attains the maximum in the flood season. Some rivers indeed carry very heavy sediment load. According to Alam (2001), the total quantity of sediment transported annually to the sea by rivers of the world is about $2*10^{10}$ tons or about 13.5 km^3 in terms of volume. Assuming that all this sediment enters into the reservoirs of the world, it would take about 481 years to fill up the estimated 6500 km^3 of the storage volume available. However, the sediment source and reservoir locations are not uniformly distributed. Experts fear that the loss could be even higher and faster if the forecasts on climate change prove to be true and the rates of deforestation in many parts of the world are not controlled. The severity of storms and rains are likely to increase as a result of global warming and this may accelerate the natural erosion rates in catchments. Global warming is also likely to exaggerate the extremes in precipitation patterns, thereby making it even more vital that the available storage capacity of reservoirs is maintained. The rates of erosion from hillsides, planted with crops, are about hundred times higher than from the same land covered with trees.

Suspended sediment load of selected rivers of the world is given in Table 12.1.

Table 12.1 Sediment load of selected rivers [Adapted from Holeman (1968)].

SN	Rivers and country	Average annual suspended sediment load, 10^6 tons	Tons/sq. km
1	Yellow, China	2080	2910
2	Ganges, India	1600	620
3	Brahmputra, Bangladesh	800	309
4	Yangtze, China	550	212
5	Indus, Pakistan	480	185
6	Amazon, Brazil	400	154
7	Mississippi, United States	344	132
8	Irrawaddy, Burma	330	127
9	Missouri, United States	240	92
10	Kosi, India	190	73

The sedimentation problem is quite severe in some countries. China has more than 80000 reservoirs that annually lose about 2.3% of storage capacity due to sedimentation. The sediment transport features for some important rivers are given in Table 12.2.

Soil erosion is considerably high in arid climates. In India, about 5333 million tonnes (16.35 t/ha) of soil is detached annually due to agriculture and associated activities and, about 29% of this is carried away by rivers into the sea. Nearly 10% of it is deposited in reservoirs resulting in loss of 1 to 2 % of the storage capacity (Dhruva Narayana, 1995). While the rivers in the Indian peninsula, such as the Krishna and the Godavari, carry about 100 ppm (parts per million), the silt carried by the Ganga often exceeds 2,000 ppm. In another North Indian river, Kosi, the silt content is much larger, being 3310 ppm. Garde and Kothyari (1986) have studied sediment yield estimation and have presented the average erosion rates for large river catchments in India (see Table 12.3).

Each sediment particle being transported by flow is affected by two dynamic forces: a horizontal component acting in the direction of flow and a vertical component due to gravity; there is also a force of water turbulence. Since the specific gravity of soil materials is about 2.65, the particles of suspended sediment tend to settle at the channel bottom, but upward currents in the turbulent flow counteract the gravitational settling. The sediment inflow and outflow in the natural river reaches is mostly in balance.

Table 12.2 Sediment transport features of selected rivers [Adapted from Qiang and Dai (1980)].

River	Drainage area (km²)	Average sediment concentration (kg/m³)	Erosion modulus (t/km²/yr)
		World rivers	
Nile	2,978,000	1.25	37
Missouri	1,370,000	3.54	159
Colorado	637,000	27.5	212
Indus	969,000	2.49	449
Irrawaddy	430,000	0.70	695
Brahmaputra	666,000	1.89	1090
Red	119,000	1.06	1092
Ganges	955,000	3.92	1519
		Rivers in China	
Huaihe	261,500	0.46	153
Liaohe	166,300	6.86	240
Pearl	355,000	0.35	260
Yangtze	1,807,200	0.54	280
Haihe	50,800	60.8	1,944
Yellow	752,400	37.6	2,480

Table 12.3 Average Erosion Rates for Large River Catchments in India

River	No. of points at which erosion rates were considered	Catchment area in 10^4 km²	Erosion rate ton/km²-yr estimated by Garde and Kothyari (1986)
Ganga	23	86.15	1969.0
Indus	4	32.13	1942.5
Brahmaputra	5	18.71	1891.0
Mahanadi	11	14.16	1287.0
Sabarmati	7	2.17	1277.0
Cauvery	5	8.79	1214.0
Krishna	7	25.0	1191.0
Godavari	10	31.28	954.0
Tapi	10	6.69	935.0
Narmada	10	9.88	906.0
Mahi	3	3.76	820.0
Luni	1	0.001	250.0

A dam on a stream channel changes the hydraulic characteristics of flow and its sediment transport capacity. As the reservoir width is much bigger than the river channel width, the velocity of flow entering into it decreases tremendously. At the same time, there is a dampening of water turbulence. All these factors contribute to make the flow unable to transport all the sediment particles and the particles begin to deposit. First, the larger suspended particles and most of the bed load is deposited at the mouth of the reservoir. The smaller particles remain in suspension for a long time and some may pass the dam with water discharged through sluices, turbines or the spillways. The deposition of coarse sediments reduces the reservoir storage and channel conveyance for water supply, irrigation, and navigation and causes extensive disturbance to streams. Suspended sediments reduce the water clarity and sunlight penetration, thereby affecting the biotic life. The settlement of sediments at the bottom of water bodies buries and kills the vegetation and changes the ecosystem.

12.1 RESERVOIR SEDIMENTATION

The accumulation of sediments is one of the principal factors that threaten the longevity of river valley projects. In fact, sometimes a project is not constructed just because the silting rate is so high that the reservoir will fill up before the investment is fully recovered. The problems of concern for planners are the rapidity of reservoir sediment deposition and the time that will elapse before the use of the reservoir storage capacity is seriously impaired. In general, a dam designer needs to determine:

a) the volume of sediments that will accumulate in the reservoir each year,
b) the distribution of sediments in the reservoir,
c) the aggradation above a reservoir, and
d) the reservoir trap efficiency.

The ultimate destiny of all reservoirs is to be filled with sediments. Reservoir planning must include consideration of the probable rate of sedimentation to determine whether the useful life of the proposed reservoir will be sufficient to warrant its construction. If the sediment inflow is large compared to the reservoir capacity, special care is needed in design and operation, otherwise the useful life of the reservoir may be short. There are instances of reservoirs being filled-up within a few years of their operation. A small water-supply reservoir in the U.S.A. was filled with sediment during the first year after its completion. Morris and Fan (1998) quote many interesting examples. The Sanmexia dam, constructed during 1957-60, was the first major dam on the middle reaches of the Yellow River. In the first 18 months after the dam closure, 1.8 billion metric tons of sediment accumulated in the reservoir, representing a trap efficiency of 93%. The sediment deposits were also found to raise the bed elevations and flood levels in the Yellow River as far as 260km upstream of the dam. The Xinghe reservoir in the Shaanxi province took two years to construct but only one year to fill with sediment. The 21.8 Mm^3 Laoying reservoir in Shaanxi province silted up even before the irrigation canal was completed. The 76 m high Warsak dam on the Kabul River in Pakistan lost 18% of its storage volume in the very first year of operation (Nagy et al., 2002).

The right approach to solve reservoir sedimentation problem has the following three components: (a) collection and analysis of field data, (b) setting up of appropriate models, and (c) development of an operational policy for the reservoir. When different operation modes are adopted for a reservoir, deposition and scour may differ considerably. To foresee what changes are likely to occur so that remedial measures could be taken as early as possible, a reliable prediction is needed before the decision is made.

The sediment deposits in a reservoir can be divided into three groups: topset beds, foreset beds, and bottomset beds as shown in Fig. 12.1. The topset beds are composed of large size sediment deposits but one may also find fine particles. These extend up to the point where the backwater curve ends. The downstream limit of the topset bed corresponds to the downstream limit of the bed material transport in the reservoir. These deposits cause a minor reduction in the reservoir storage capacity. Foreset deposits represent the face of the delta deposit advancing in the reservoir towards the dam. It is a transition zone having steeper slopes and decreasing grain size. The bottomset beds consist of fine sediments which are deposited beyond the delta by turbidity currents or non-stratified flow. Note that this particle distribution may change due to reservoir drawdown, slope failures and extreme floods. In a reservoir with significant water level fluctuations, the nature of deposition will depend on these fluctuations because these can move the topset and foreset beds further downstream fairly quickly. During a major earthquake, sediment deposits may be subjected to liquefaction and may move abruptly and destroy water intake towers and other structures in the reservoir (Alam, 2001).

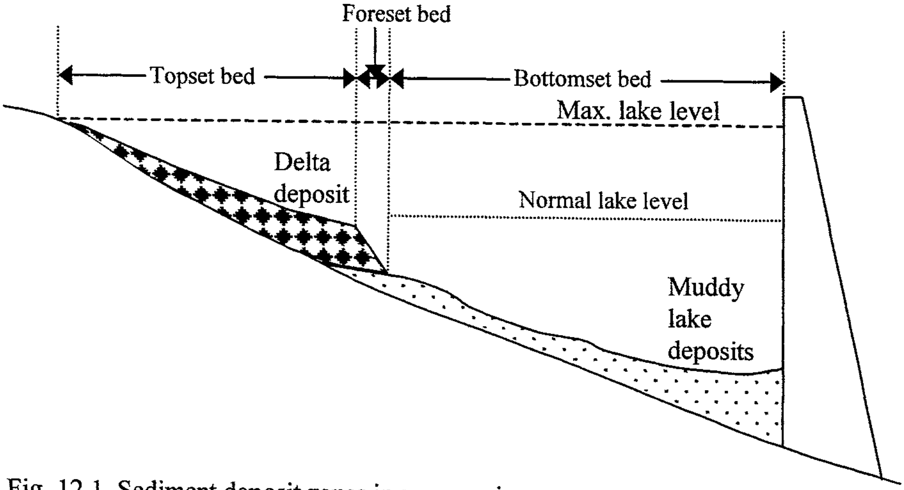

Fig. 12.1 Sediment deposit zones in a reservoir.

For proper allocation of the storage space and management of a reservoir, knowledge about the sediment deposition pattern in various zones is essential. It is essential to periodically conduct surveys and assess the sedimentation rate in a reservoir. With the correct knowledge of the sedimentation processes taking place in a reservoir, remedial measures can be undertaken well in advance.

12.1.1 Problems due to Reservoir Sedimentation

The sediments deposited in the reservoir are an indication of the sediment yield of the entire catchment. The problems due to sedimentation can take place upstream, downstream, and in the reservoir. The pattern of deposition depends on several factors, such as size and texture of sediment particles, characteristics of reservoir outlets, size and shape of the reservoir, and its operation schedule. Generally, coarser sediments deposit first in the reservoir headwaters and finer particles are transported by density currents down to the dam.

Sedimentation reduces the storage capacity of reservoirs and thereby, their ability to conserve water for various intended purposes. Consequently, the frequency and magnitude of failures increases. Sediment deposition may also hamper the operation of outlet structures. Due to sediments brought by a flood, the outlet structures of the Guayabal irrigation dam in Puerto Rico remained buried for several days and it was not possible to deliver water for irrigation. Sedimentation also reduces the survival of aquatic species. It results in increased evaporation due to the higher exposure area of the water. In one instance, it was found that the additional loss through evapotranspiration due to increased vegetation was about 10% of the annual supply.

12.1.2 Factors Influencing Reservoir Sedimentation

Sediment transport by rivers varies from near zero during dry weather to extremely large quantities during major floods. Hence, it is difficult to predict the sediment accumulation during a short period of time. The main source of knowledge of the reservoir sedimentation rates are surveys of sediment accumulation in reservoirs that have been studied for many years. These surveys indicate the specific weight of the settled sediments and the percentage of entering sediment that is deposited in the reservoir. Further, the sediment accumulation during a period of a few years may not indicate the long term sedimentation rate.

The two dominant factors that influence the rate of silting in any storage reservoir are: (a) capacity to inflow (CI) ratio, and (b) sediment content in the water flowing in. The other factors that affect the long-term loss of storage capacities are the texture and size of the sediment, trap efficiency, size, shape, and length of the reservoir, and the method of reservoir operation. The CI ratio is the ratio of reservoir storage capacity to mean annual inflow. A reservoir having this ratio more than 50% is considered hydrologically large and may have significant carry-over. If the CI ratio is large, the trap efficiency will also be large. Note that the sediment inflow depends on the catchment area too. All other things remaining the same, a dam of the same capacity in the upper catchment will have a higher rate of silting compared to a dam lower down the valley.

The two principal factors mentioned above have a complete range of interplay. A reservoir having a small CI ratio and small sediment inflow and the other having a large CI ratio and large sediment inflow may have more or less the same average annual percentage loss of capacity. With a high CI ratio and high sediment content in inflow, a high rate of silting can be expected. On the other hand, a high CI ratio and low sediment content in inflows will result in a small rate of silting.

The detention period denotes the time required to replenish water in the reservoir. It is the ratio of reservoir storage capacity and the inflow rate over a specified duration. For a reservoir, this ratio varies with season. In a hydrologically small reservoir, the detention period during a big flood may be of the order of a few hours while during a dry season, it can be up to several months. A hydrologically small reservoir will have a short detention period and the flood water will not stay in the reservoir for a long time.

To evaluate the effect of each of these factors and to serve as a guide for future planning, systematic capacity surveys of reservoirs should be undertaken at regular intervals. It further helps in planning corrective measures by way of the catchment area treatment, if surveys reveal abnormal deviations. The characteristics of sediments, particularly the particle size distribution, help determine their unit weight and location of deposition within the reservoir.

12.1.3 Trap Efficiency

The trap efficiency of a reservoir is the ratio of sediment retained in the reservoir to the sediment brought into it. Thus, it is the percentage of the total incoming sediment retained in the reservoir. The trap efficiency primarily depends on the sediment characteristics (particle size distribution and the behavior of the finer fractions under varying concentration, temperature, etc.), the detention time of inflow, method of operation, and age of reservoir. The detention time depends on: a) the CI ratio, b) the shape of the reservoir basin, and c) the type of outlets and operation schedule. Clearly, greater the period of retention (similar to detention period above) in a given pool, lower the transit velocity and turbulence, the higher will be the percentage of deposition of incoming sediment. The *sedimentation index* is the ratio of the period of retention to the mean water velocity through the reservoir. The *period of retention* is equal to the reservoir capacity (m^3) divided by the average daily inflow to the reservoir (in m^3/s). A small reservoir on a large stream passes most of its inflow so quickly that finer sediments do not settle but are discharged downstream. A larger reservoir, on the other hand, may retain water for several years and the outflow from it may be completely devoid of suspended sediment. The trap efficiency of a reservoir decreases with age as the reservoir capacity is reduced by the sediment accumulation and complete filling may require a very long time.

The CI ratio is an indicator of the period of retention. The reservoirs with CI ratios less than unity are called seasonal storage while those with CI ratio over unity are known as carry over reservoirs. When CI ratio > 1, water is rarely spilled from the reservoir. Taking into consideration the effect of seepage and evaporation losses, the trap efficiency of such reservoirs will obviously be close to 100 %.

When the estimated sediment accumulation is a substantial percentage of the reservoir capacity, it may be necessary to analyze the trap efficiency for some incremental periods of the reservoir life. Theoretically, the reservoir trap efficiency will progressively decrease, once storage has begun. However, it is generally not practical to analyze the trap efficiency by increments of less than 5 years. While allocating space for dead storage during the planning stages, the trap efficiency is usually considered about 90%.

The trap efficiency can be computed from the inflow and outflow data of sediments. The outflow of sediments can be assessed from the observations downstream to the dam immediately after the outlets. Empirical relations have also been derived based on the trap efficiency actually observed.

Brune (1953) analysed data from 44 reservoirs in the U.S.A., 40 being normal ponded reservoirs with catchment areas varying from 0.098 km^2 to 478000 km^2 and the CI ratio ranging from 0.0016 to 2.05. Besides normal ponded reservoirs, the analysis included 2 desilting basins and 2 semi-dry reservoirs. Desilting basins are shallow reservoirs normally constructed at a point where the stream gradient suddenly decreases. The average effective depth of such a reservoir is generally less than 1.2 m. The semi-dry reservoirs are those which are not allowed to fill the available storage capacity due to the non-acquisition of the full land and thereby restricting the operation of the dam. Besides the trap efficiency, data was also collected on the capacity, annual inflow, shape of the reservoir basin, method of operation, location and characteristics of outlets, and density-current, if any.

This analysis brought out that the laws of sediment deposition are the same for all types of reservoirs, and the factors influencing the trap efficiency are the same irrespective of the size of the reservoir. The observations showed that it is probable that reservoirs having a very low CI ratio may alternately fill and scour, depending on the stream flow conditions, and may have a trap efficiency of zero or less during periods of scour. In many dry and semi-dry reservoirs, the available capacity is not filled but is operated with a small storage so that most of the sediment flows out of the dam without being trapped. Thus, although the CI ratio may be high, the trap efficiency can be low. Even in carry-over reservoirs, if the operation is adjusted so as to allow a major portion of the inflow through the outlets, the trap efficiency may be brought to nearly 60% with a CI ratio of 1.7. Under normal operating conditions, the trap efficiency would be of the order of 90%.

Brune (1953) presented a set of envelope curves between CI ratio and trap efficiency, shown in Fig. 12.2. This figure shows a semi-logarithmic curvilinear relation between trap efficiency and the CI ratio. Note that the data from reservoirs in the United States were used to develop these graphs. Murthy (1977) summarized the important conclusions on the trap efficiency:

1. The CI ratio shows a good correlation with the reservoir trap efficiency.
2. Although reservoirs are unlikely to have a trap efficiency of zero or 100 %, under actual field conditions, trap efficiencies of zero or 100 % are sometimes found.
3. Efforts at sluicing or venting sediment from reservoirs vary in effectiveness. Proper planning and correct timings of venting operations to intercept gravity under-flows can treble or quadruple the amount of sediment cleared from a reservoir.
4. Desilting basins, largely because of their shape, have much higher trap efficiencies than do normal ponded reservoirs. For desilting basins not equipped with mechanical removal of sediment, trap efficiencies above 90 % appear to prevail with a CI ratio as low as 0.02. With mechanical removal of sediment, such trap efficiencies may be found in even lower CI ratio ranges of as low as 0.001.
5. Semi-dry reservoirs may be expected to have much lower trap efficiencies than do

normal ponded reservoirs. Even carry-over storage reservoirs, if operated so as to allow for large flows of water to pass unrestricted through the dam, may have trap efficiencies in the range of 60 % rather than above 90 %, as would be expected with normal operation.

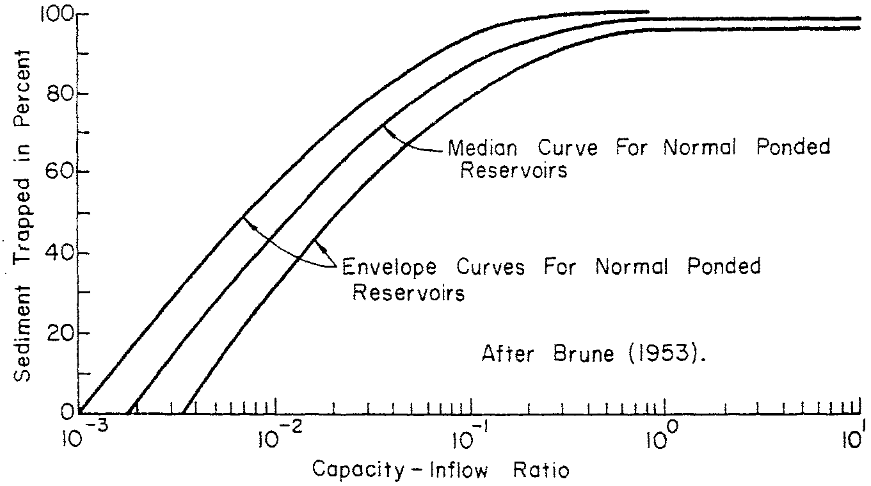

Fig. 12.2 Reservoir trap efficiency curves by Brune (1953).

Table 12.4 summarizes the trap efficiency and other relevant data for some Indian reservoirs as reported by Murthy (1977).

Table 12.4 Capacity, CI ratio, and trap efficiency of a few Indian reservoirs [Source: Murthy (1977)].

Name	Capacity (10^6 m^3)	CI Ratio	Trap Efficiency
Matatila	1132.7	0.187	67-90
Hirakud	8100	0.2	65-90
Gandhi Sagar	4700	0.66	100
Bhakra	9800	0.66	99

A relationship between sediment release efficiency and sedimentation index was developed by Churchill (1948). The Churchill's curve is shown in Fig. 12.3.

12.1.4 Sedimentation and Life of a Reservoir

The term *life of a reservoir* appears to be a misnomer, since the reservoirs do not have a single well defined life which denotes two functional states: *ON* and *OFF*. Rather they show a gradual degradation of performance. Sedimentation and the consequent reduction of capacity is a gradual process, which can be classified in various phases. From the point of

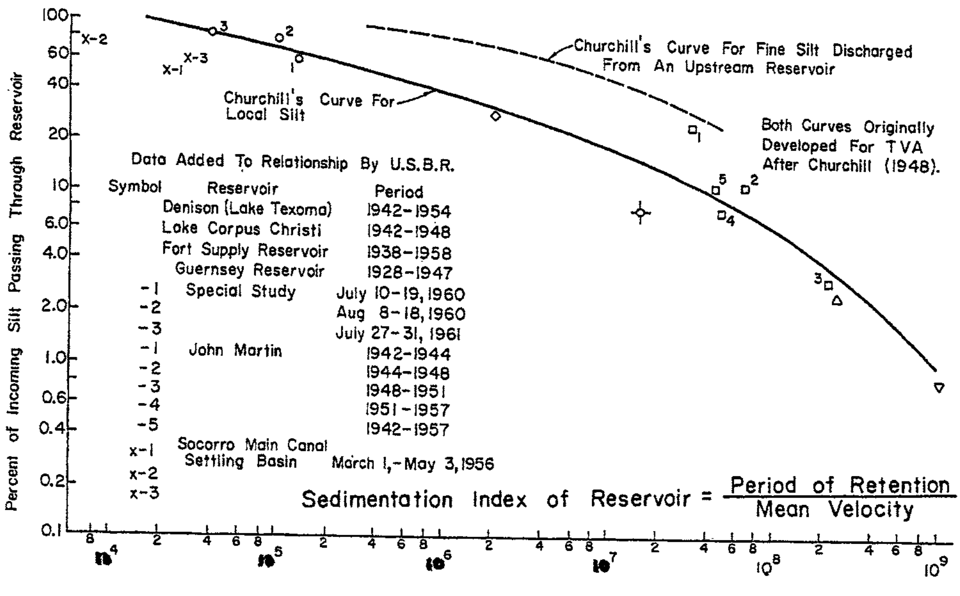

Fig. 12.3 Reservoir trap efficiency curve by Churchill [Source: Borland (1971)].

view of operation, it is important to find when the sedimentation reaches the extent that the satisfaction of the purpose of the reservoir begins to suffer. At this stage, may be lesser command area can be serviced or lesser power can be generated. The flood control pool is at the top of the conservation pool and this purpose begins to suffer after the sediments largely occupy the conservation pool. Thus, the 'life' of a reservoir for different purposes will be affected at different times. Murthy (1977) defined the following terms connected to the life of a reservoir.

Useful Life: It is the period during which the capacity occupied by sediments does not prevent the reservoir from serving its intended primary purpose. It is said to be over when the reservoir cannot meet the intended commitments.

Economic Life: This is determined by the point of time after which the effect of various factors, such as physical deterioration by sedimentation, changing requirements for project services, etc., cause the operating costs of the reservoir to exceed the additional benefits from its continuation. In other words, this is the period during which it can be operated with economic efficiency.

Usable Life: This is the period of time over which the reservoir can continue to serve some of the purposes, although to a limited extent, even after the expiration of its economic life, singly or in conjunction with additional facilities created for the purpose.

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

Full Life: It is the number of years required for the reservoir capacity to be fully depleted by sedimentation.

Half Life: This is the time over which half of the reservoir storage capacity is expected to be occupied by sediments. Note that the trap efficiency decreases with storage capacity and hence the entire storage will not be filled in time which is twice the half life. Usually, a half-life is the time after which the adverse effects of sedimentation begin to affect the operation of a conservation reservoir.

According to the approach incorporated in the Indian Standard IS: 12182 (1987), the life of a reservoir has five phases. The end of Phase-I is said to occur at the end of the period in which the reservoir is capable of yielding the full planned benefits. The Phase-II would depict a period when the operation of the reservoir is also trouble free, in regard to sedimentation, although the efficiency of the reservoir gradually reduces, and management measures to adjust to the reduction are required. The Phase-III would be a period of troubled operation, and unless some new engineering solutions are implemented, the project may have to be given up in phase-IV or phase-V.

12.1.5 Allocation of Space for Sediments

The most common procedure to deal with the sediment problem is to designate a portion of the reservoir capacity as sediment storage. This, however, is a negative approach that in no way reduces the sediment accumulation but merely postpones the date when it becomes serious. Since sediment is deposited all through the reservoir, the allocation for sediment storage cannot be exclusively the dead storage but must also include some useful storage. Actually, the reservoir sedimentation cannot be totally prevented, but it can be retarded. One way of doing this is to select a site where the sediment inflow is naturally low. Some basins are more prolific sources of sediment than others because of soil type, land slopes, vegetal cover, and rainfall characteristics. If an alternative site exists, prolific sediment sources should be avoided.

After a site has been selected, the reservoir capacity should be made large enough so that its useful life is sufficient to warrant the project. Although the trap efficiency of a large reservoir is high, it does not increase linearly, and the useful life of a large reservoir is longer than that of a small reservoir, if all other factors remain constant.

12.2 LOSS OF STORAGE CAPACITY

After completion of a dam, a backwater region is formed. Sediment coming from upstream starts to deposit and the storage capacity of the reservoir decreases as time passes. According to Mahmood (1987), world wide, reservoirs are losing storage at an annual rate equivalent to 1 % of the storage capacity which amounts to about 65 km^3 per year. The replacement cost of this storage is indeed very high. According to estimates by Crowder

(1987), the rate of loss of the reservoir storage in the United States is about 0.22% per year which is equivalent to 2020 million m^3 per year. Based on the weighted average data of 144 reservoirs in India, the annual loss of the gross storage is about 0.44 %.

12.2.1 Rate of Loss of Storage Capacity

Table 12.5 gives sedimentation in 20 representative reservoirs in China. Approximately 8,060 Mm^3 of sediments were accumulated in the reservoirs, and 19.2 % of the design capacity was lost, even though most of the reservoirs had been in operation for less than 20 years. Considering the fact that the amount of material washed out from a basin is a function of the erosion rate and drainage area of the basin, the following empirical formula was derived (Deyi and Fan, 1991):

$$R_s = 0.0002\, G^{0.95}\, (F/S)^{0.8} \qquad (12.1)$$

in which R_s is the % average loss rate of reservoir capacity per year; G is the average soil erosion from the basin in t/km^2 /year; F is the drainage area in m^2, and S is the reservoir capacity in m^3.

Table 12.5 Sedimentation in some reservoirs in China [Source: Deyi and Fan (1991)].

S. N.	Name of Reservoir	River	Drainage area (km^2)	Dam height (m)	Design capacity (Mm^3)	Year of Survey	Total sediments (Mm^3)	% capacity lost
1	Liujiaxia	Yellow	181,700	147	5,720	1968-78	580	10.1
2	Yanguoxia	Yellow	182,800	57	220	1961-78	160	72.7
3	Bapanxia	Yellow	204,700	43	49	1975-77	18	35.7
4	Qingtongxia	Yellow	285,000	42.7	620	1966-77	485	78.2
5	Sanshengong	Yellow	314,000	N A	80	1961-77	40	50
6	Tiangiao	Yellow	388,000	42	68	1976-78	7.5	11
7	Sanmenxia	Yellow	688,421	106	9,640	1960-78	3,760*	39
8	Bajiazui	Pu	3,522	74	525	1960-78	194	37
9	Fengjiashan	Qian	3,232	73	389	1974-78	23	5.9
10	Heisonglin	Yeyu	370	45.5	8.6	1961-77	3.4	39
11	Fenhe	Fen	5,268	60	700	1959-77	260	37.1
12	Guanting	Yongding	47,600	45	2,270	1953-77	552	24.3
13	Hongshan	Xiliao	24,486	31	2,560	1960-77	475	18.5
14	Naodehai	Laoha	4,501	41.5	196	1942	38	19.5
15	Yeyuqn	Mi	786	23.7	168	1959-72	12	7.2
16	Gangnan	Hutuo	15,900	63	1,558	1960-76	235	15.1
17	Gongzui	Dadu	76,400	88	351	1967-78	133	38
18	Sikou	Bailong	27,600	101	521	1976-78	28	5.4
19	Danjiangkou	Han	95,217	110	16,050	1968-79	879	5.6

*At water level of 335 m.

Observations show that in the reservoirs which have a small sluicing capacity with respect to normal floods and which have no reservoirs above them, the siltation rate is comparatively high in the first 15-20 years and thereafter it falls off and may ultimately become negligible. From the data of reservoir capacity surveys, Shangle (1991) found that the sedimentation rates in major reservoirs (storage > 100 million m^3) in India that have completed more than 50 years of their useful life varied from 0.30 to 4.89 Ha-m/100 sq. km/year. The rate for those major reservoirs that have completed less than 50 years of their useful life was found to vary from 0.34 to 27.85 Ha-m/100 sq. km/year. The data given in Table 12.6 also shows that the rate of siltation of a reservoir falls with time.

Table 12.6 Rate of siltation of some Indian reservoirs [Source: Central Water Commission, New Delhi, India].

S.N.	Name of reservoir (State)	First period of 10 years (A)	Rate of siltation	Last period of 10 years (B)	Rate of siltation	Total period between mid points of A and B	% decrease in rate of siltation in the total period	Percentage decrease in rate siltation per year
1.	Panchet Hill (Bihar)	1956-66	0.973	1986-96	0.313	30	67.83	2.261
2.	Maithon (Bihar)	1955-65	1.170	1984-94	1.132	29	03.24	0.117
3.	Pong (HP)	1974-84	2.558	1988-98	1.350	14	47.22	3.383
4.	Tungabhadra (Karnataka)	1953-63	0.602	1983-93	0.226	30	62.46	2.082
5.	Hirakud (Orissa)	1967-77	0.657	1984-94	0.562	17	14.46	0.851
6.	Bhakra (Punjab)	1958-68	0.633	1988-98	0.663	30	-	-
7.	Lower Bhavani (TN)	1953-63	0.306	1973-83	0.246	20	19.60	0.980
8.	Vaigai (TN)	1958-68	0.409	1973-83	0.380	15	07.10	0.473
9.	Matatila (UP)	1956-66	0.849	1984-94	0.340	28	59.95	2.141
10.	Dhukwan (UP)	1907-17	0.042	1970-80	0.012	63	71.43	1.138

A possible explanation is that the obstruction by the dam causes the dips and flanks of the storage basin to fill up with silt in early years. A stage reaches when the river section adjusts itself to carry the normal discharge and the disposal of suspended load in the area of the reservoir is harmonised with the condition of the flow. Besides, the progressive development of deltas above the reservoir helps in trapping of some of the silt load. Shrinkage and settlement of deposited silt also takes place with time due to superimposed loads of additional silt load. This results in reduction in silt volume thereby reducing the sedimentation rate. However, a complete explanation of this behavior is not available.

The prediction of sediments which are likely to be deposited over a time horizon is necessary for many purposes. There are many empirical relations in the literature to predict the number of years in which the reservoir will fill completely. This number will depend on the reservoir capacity and variables on which the sediment yield depends. For example, Garde (1995) provides the following equation to estimate the number of years (T_0) in which the reservoir will completely fill if all the sediment entering into the reservoir stays there:

$$T_0 = 3.789 \times 10^{-7} A^{0.886} p^{2.869} / (C^{1.771} D_d^{1.819} F_c^{8.678}) \tag{12.2}$$

where A is the catchment area in km^2, p is annual precipitation in cm, C is the reservoir capacity in Mm^3, D_d is the drainage density in km^{-1} and F_c is the erosion factor given as

$$F_c = (0.2A_1 + 0.4A_2 + 0.6A_3 + 0.8A_4 + A_5) / (A_1 + A_2 + A_3 + A_4 + A_5) \tag{12.3}$$

where A_1 ...A_5 are the areas (in km^2) of closed and dense forest, unclassed forest, arable area, scrub and grass area and waste area, respectively. Murthy (1977) proposed the following equation to relate the sediment load in dead storage as a percentage of the total load, S, versus the dead storage as a percentage of the total capacity C_l for four types of reservoirs:

$$S = KC_l^N \tag{12.4}$$

The values of K and N for the four types of reservoirs are:

Type	Description	K	N
I	Lake	3.39	0.78
II	Flood plain in foot hill	9.33	0.56
III	Hill	25.12	0.35
IV	Gorge	32.36	0.30

It must be emphasized that such methods do not consider all the variables on which the deposition pattern depends and hence, give only approximate results. These relations for regions other than those for which data were used in developing them should be applied with caution.

12.2.2 Unit-Weight of Deposited Sediments

The sediment load obtained by the measurements of suspended silt from the streams is usually expressed in weight and to convert it to space occupied, the weight-volume relationship has to be established. The unit-weight of sediments is the dry weight (kg) per unit volume (cubic meter) of the material. The unit-weight of a reservoir deposits varies widely, and the density of the deposited sediment has been observed to vary from 500 to 2000 kg/m^3. If unit-weight estimates are wrong, the silt load will not be correctly estimated. Therefore, the correct assessment of the density of deposited sediment is necessary. The following classification of sediment according to size is normally used.

Sediment Type	Size Range (mm)
Clay	Less than 0.004
Silt	0.004 to 0.0625
Sand	0.0625 to 2.0

Important factors that influence the unit weight of the deposited sediment are the manner in which the reservoir is operated, the texture and size of sediment particles, and the compaction or consolidation rate. Other factors, such as density currents, thalweg slope, and the effect of vegetation in head reaches of the reservoir, are less influential. The reservoir operation is the most influential of these factors. If a reservoir is operated, lowering its levels from time to time, the deposited sediment gets exposed to sun and air and gets dense. In case of detention basins where flood is temporarily held and evacuated as early as possible, there will be considerable time gap between floods so that the sediment deposited by previous floods gets dried up and is consolidated before the next flood. The degree of consolidation depends on the weight of the overlying material, its exposure, sediment size, and time. The reservoir which is always filled up has a low density of deposit. Power and irrigation reservoirs belong to the intermediate class. In multipurpose reservoirs which are operated depending on the various requirements, the determination of sediment density becomes complicated. Generally, lower densities are observed in the vicinity of the dam under submerged conditions while higher densities are noticed in the upstream portions of reservoirs.

The size of the incoming sediment particles has a significant effect on the unit-weight. Sediment deposits composed of silt and sand will have a higher unit-weight than those in which clay predominates. Based on the results of the unit-weight and size distribution analysis of 1300 samples, Lara and Pemberton of U.S.B.R. developed a method to estimate the initial unit-weight of sediment deposits when the particle size of the incoming sediments and the proposed reservoir operation schemes are known. Reservoir operations were classified according to different types as follows:

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

After the reservoir type has been selected, the unit-weight of the sediment deposits can be estimated using the following equation:

$$\gamma = 16.05(W_c P_c + W_m P_m + W_s P_s) \qquad (12.5)$$

where γ is unit-weight in kg/m^3; P_c, P_m, P_s are percentages of clay, silt, and sand of the incoming sediment respectively; and W_c, W_m, W_s are the coefficients of clay, silt, and sand, respectively, which may be obtained from the following table (Murthy 1977):

Reservoir Type	W_c	W_m	W_s
I	26	70	97
II	35	71	97
III	40	73	97
IV	60	73	97

Example 12.1: The particle size analysis for a type I reservoir shows 23 % clay, 40 % silt, and 37 % sand. Estimate the unit weight of sediments.

Solution: The unit weight is computed as

$$\gamma = 16.05[26(0.23)+ 70\ (0.40) + 97(0.37)] = 16.05(5.98 + 28.00 + 35.89)$$
$$= 1121.4\ \text{kg/m}^3$$

12.2.3 Aggradation and Degradation

A river reach is in equilibrium when the sediment load entering into it is equal to that going out. If, due to some reason, the sediment entering is more than sediment leaving, the balance of sediment is deposited in the reach. Aggradation refers to the up-rising of the riverbed to a new elevation and profile due to sediment deposition. The major consequences of reservoir aggradation are:

- delta deposits leading to reduced channel capacities;
- the rise of the backwater profile of the channel upstream from the reservoir, thus creating problems for riparian villages besides being eyesores;
- adverse environmental effects, such as formation of stagnant pools in adjacent lands; and
- deterioration of water channels due to larger sediment concentration, and infestations of phreatophytes, such as salt cedars.

It is necessary to determine the elevation up to which sediments will accumulate so as to fix the location of undersluices and other outlet works. If the reservoir is to be used for recreational purposes then the location of these facilities should be decided keeping in view the sediment accumulation.

The water released from a dam is relatively free of sediments and has the capacity to erode and transport sediments. If the downstream channel consists of loose material, the same is eroded by this water resulting in lowering of the bed level. This is known as degradation and in some cases, this may extend for hundreds of kilometers downstream. This may disturb the river environment and may cause other problems in the downstream areas. Garde and Rangaraju (1977) cite many examples of such problems. The Islam barrage on River Sutlej failed due to degradation. A subsidiary weir had to be constructed downstream of the Naga Hemadi barrage on the Nile River to control degradation. Due to degradation below the Hoover dam on the Colorado River, 150 million cubic yards of material had been removed from the channel over a distance of 150 km during 1935-51. Degradation may also endanger the foundations of bridges.

12.2.4 Distribution of Sediments in Reservoirs

An understanding of the pattern or profile of sedimentation in the reservoir helps in predicting the extent to which services will be affected at various times and the remedial actions to be taken. In planning and design stages, the designer is interested to know up to what height the sediment will accumulate in a given period to fix up the sill elevation of the outlets and the penstocks gate elevation, etc. The pattern is also needed to mark the region where delta would be formed, and backwater levels will increase. The backwater levels are important particularly if the reach happens to be in a developing area. Finally, the pattern is necessary to locate spots for recreational facilities, such as swimming and boating.

A commonly used empirical method to estimate the new reservoir profile is discussed next.

12.2.5 Empirical Area Reduction Method

Based on the elevation-capacity characteristics, reservoirs are classified into four types, namely, (a) gorge, (b) hill, (c) flood plain-foot hill, and (d) lake. The empirically derived sediment distribution curves are used to distribute the sediment throughout the reservoir section. The *Empirical Area Reduction* method, as revised by Lara (1962), is the most popularly used method to predict the new reservoir bed profile. It is necessary to first estimate the amount of sediment deposited in the reservoir. This method is illustrated using an example drawn from Murthy (1977). The example data in Table 12.7 pertains to a reservoir whose original capacity was 8253.3 ha-m. The top of the conservation zone was 15.43 m above the original bed near the dam. A sediment survey showed that the sediment deposition was 1143.9 ha-m.

The steps of computations are as follows.

1. Plot the depth vs. the original reservoir capacity on a double log paper with capacity on the x-axis and depth on the y-axis. Fit a straight line to the data and compute its slope *m*. If a single line does not represent the behavior, take the slope of the portion where the water level lies most of the time. On the basis of *m*, the reservoir is classified in the following classes:

m	Reservoir shape	Type
3.5 – 4.5	Lake	I
2.5 – 3.5	Floodplain – foothill	II
1.5 – 2.5	Hill and gorge	III
1.0 – 1.5	Gorge	IV

The type curves developed by USBR are shown in Fig. 12.4. From the curve of Type I reservoir, it is clear that about 50% sediments accumulate in 30 % (70 to 100%) of the shallow depth zone; thus in the lake–type reservoir, more sediments are deposited in the shallow water region. In contrast, in the gorge type reservoir, about 50% sediments

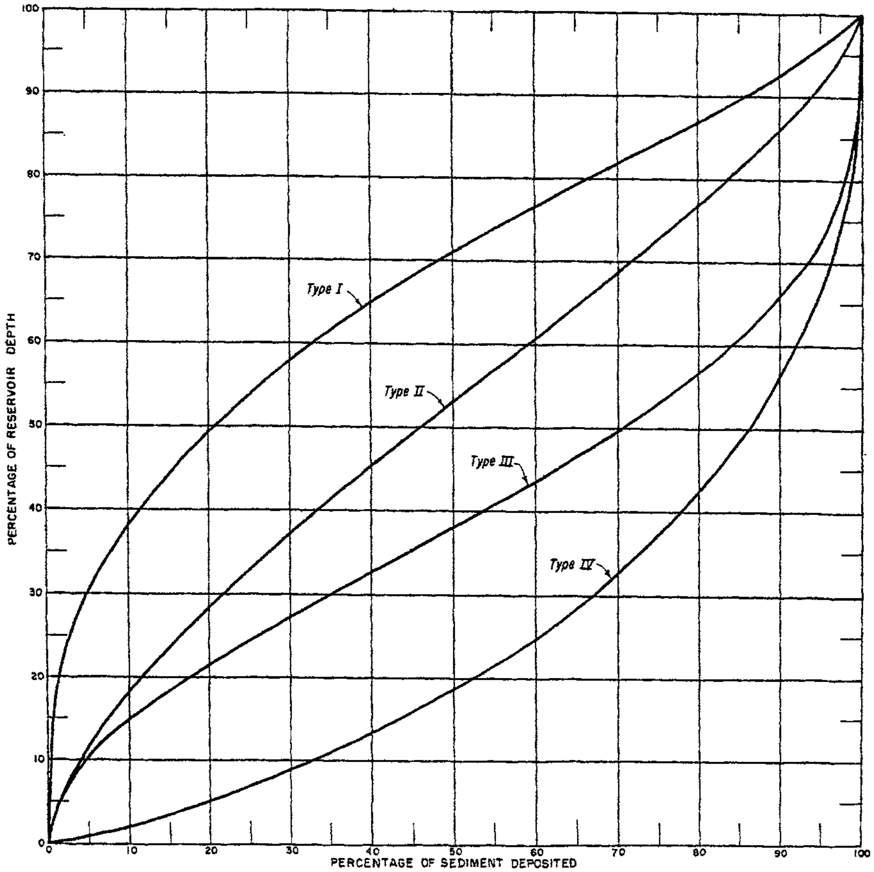

Fig. 12.4 Reservoir storage design curves [Source: Strand (1977)].

accumulate in 20% (0 – 20%) depth and such reservoirs have a propensity to accumulate sediments in deeper zones. The sediment distribution depends on the operation of the reservoir and from this consideration, Morris and Fan (1998) classify the reservoir as stable pool, moderate drawdown, considerable drawdown, or normally empty. They have provided the following table to determine the weighted reservoir type by giving equal weight to the shape and operation:

Reservoir operation	Operational class	Shape class	Weighted class
Sediment submerged (continuous high pool level)	I	I	I
		II	I or II
		III	II
Moderate drawdown	II	I	I or II
		II	II
		III	II or III
Considerable drawdown	III	I	II
		II	II or III
		III	III
Normally empty	IV	All	IV

The type should be selected by giving due importance to that aspect of the reservoir, i.e., shape or operation, whichever has more influence on sedimentation. In most river basins, the grain size distribution is not an important factor in influencing sediment distribution. Only in those cases where there is a choice between two type classes, the following table can be used to finalize the type:

Predominant grain size	Type
Sand or coarser	I
Silt	II
Clay	III

The reservoir under consideration is a Type II reservoir.

2. The original elevation-capacity data are used to compute the values of F (column 4) at different reservoir elevations in the deeper part (where elevation is lesser):

$$F = (S - V_h) / H\,A_h \tag{12.6}$$

where S is the total sediment deposition (1143.9 ha-m), H is the original depth of reservoir below the conservation pool (15.43m), and V_h and A_h are capacity and area at elevation h.

3. The decimal values of relative depth are calculated using:

$$p = (h - h_{min})/H \tag{12.7}$$

where h_{min} is the original bottom elevation (560.52m) of the dam.

4. Plot the F and p values on the type curve graph. The intersection of this curve with the curve representing the reservoir type defines the point known as the *new zero elevation* (NZE). In this case the intersection point p_0 is 0.237 and the new zero elevation $h_0 = p_oH + h_{min} = 0.237*15.43 + 560.52 = 564.177$m. From the original curve, the corresponding area A_0 is 79.72 ha.

5. To estimate the sediment distribution within various zones, the value of the relative sediment area a at each depth p (column 6) is computed as:

$$a = b\,p^c\,(1-p)^d \tag{12.8}$$

The values of b, c, and d depend on the type of the reservoir as given below:

Type	b	c	d
I	5.047	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

Table 12.7 Illustrative example of empirical area Reduction Method.

Original Survey Data			F	Relative		Computed sediment distribution			Revised	
Elevation h (m)	Area A_h $(10^4 m^2)$	Capacity V_h $(10^6 m^3)$	value	Depth P (%)	Area a	Area $(10^4\ m^2)$	Volume increment $(10^6 m^3)$	Cumulative volume $(10^6 m^3)$	Area $(10^4\ m^{2)}$	Capacity $(10^6\ m^3)$
1	2	3	4	5	6	7	8	9	10	11
575.95	1394.14	8253.30		1.000	0.000	0.000	0.00	1143.90	1394.14	7109.40
574.55	1197.87	6442.74		0.909	0.875	72.44	54.12	1089.78	1125.43	5352.96
573.02	1006.45	4771.17		0.180	1.113	91.86	124.84	964.93	914.59	3806.23
571.50	833.65	3372.66		0.711	1.230	101.57	146.98	817.95	732.07	2554.71
569.97	679.06	2226.30		0.613	1.277	105.62	157.44	660.51	573.44	1565.79
568.45	513.95	1316.10		0.514	1.267	104.41	159.90	500.61	409.54	815.49
566.93	366.64	651.90	0.087	0.415	1.210	99.95	155.59	345.01	266.69	306.88
565.55	191.41	268.63	0.296	0.326	1.117	92.27	131.61	213.40	99.15	55.22
564.18	79.72	95.81	0.852	0.237	0.975	79.72	117.59	95.81	0	0
562.35	19.42	984	3.785	0.119	-	19.42	85.97	9.84	0	0
560.52	0	0	0	0	-	0	9.84	0	0	0

Adapted from Murthy (1977).

For this dam (Type II) and $p = 0.237$, the value of a (at p_0) is 0.979.

6. The area correction factor is $A_0/a_{p0} = 79.72*10^4/0.979 = 81.43*10^4\ m^2$.

7. The area at each reservoir elevation (column 7) occupied by the sediment is obtained by multiplying the relative sediment area (column 6) by the area correction factor. Note that below NZE, the areas in columns 7 and 2 are equal.

8. For each elevation above NZE, the sediment volume (column 8) is computed by the end area method. Below the NZE, the sediment takes the entire space and hence the sediment volume equals the reservoir capacity.

9. The cumulative volume of the sediment deposited (column 9) is obtained by summing the values in column 8. The total volume of sediment should be approximately equal to the value used in the beginning of computations.

10. The revised area and volumes (columns 9 and 10) are found by subtracting column 7 from the original area (column 2) and column 9 from the original volume (column 3).

These computations can be easily carried out using an electronic spreadsheet.

12.2.6 Economics of Reservoir Sedimentation

The consequences of reservoir sedimentation ultimately lead to a gradual reduction in benefits from the reservoir. The extent of loss depends on the type and nature of purposes being served and the rate of loss of the storage capacity. Gunatilake and Gopalakrishnan (1999) worked out the cost of reservoir sedimentation in Mahaweli reservoirs in Sri Lanka. The total cost was composed of the loss of irrigable area, hydropower production loss, cost of water purification, and fisheries yield loss. The total cost of sedimentation was estimated as $838040 as of 1993 (see Table 12.8) and it is likely to increase to $7604710 within a 50-year period. The expenditure on this project is nearly $1 billion. The present values were calculated using a 6% discount rate. Clearly, the loss of hydropower generation capacity is the most significant category of the cost of sedimentation in the Mahaweli reservoirs.

Table 12.8 Cost of sedimentation in Mahaweli reservoirs [Source: Gunatilake and Gopalakrishnan (1999). © Taylor & Francis Ltd. (www.tandf.co.uk/journals). Used by permission].

Year	Irrigable area loss ($000s)	Hydropower production loss ($000s)	Cost of water purification ($000s)	Fisheries yield loss ($000s)	Total cost of sedimentation ($000s)
1993	62.14	453.87	198.17	119.90	838.04
2002	133.09	885.91	236.83	119.90	1380.47
2012	211.92	1365.95	288.69	119.90	1992.25
2022	290.76	1846.00	351.92	119.90	2615.61
2032	369.59	2326.05	428.98	119.90	3253.10
2042	448.42	2806.09	522.93	119.90	7604.71
Present value	2693.73 (10.2%)	17592.75 (66.6%)	4230.29 (116.0%)	1189.85 (7.2%)	26406.62 (100%)

12.3 SEDIMENT YIELD OF WATERSHEDS

The major causes of erosion of the sediment that enters the reservoirs are rainfall, discharge, or natural geological reasons. The erosion rate is expressed in terms of the mass of soil removed per unit area per unit time (ton/km^2/year). The soil erosion, transport, and deposition processes are important for design and management of WRD projects as well as for structures which interact with water, e.g., bridges. The rocks may change in character, break, decay, and turn into soil by chemical and mechanical actions known as *weathering*. The process of loosening and removal of soil and rock from any part of the earth surface is known as *erosion*. The human activities influence hydrological processes in a watershed and can accelerate or decelerate erosion.

Soil erosion caused by water can be divided into the following categories: sheet erosion (due to forces of rain drop impact and surface runoff), gully erosion (by small channels of about 15 to 20 cm deep), channel erosion (of banks and beds by perennial or intermittent streams), flood erosion (due to the flow of flood water on plains), and mass movement (landslides, slope failures, avalanches, etc.).

The delivery of eroded material from the place of origin to any downstream point is a complex process conditioned by variations in watersheds characteristics, such as size, topography, slope, land cover, degree of channelization, hydrologic and hydraulic factors, etc. The sediment content of the flow is a result of many inter-related factors of which the following are the most significant:

a) the source and character of runoff,
b) the aerial extent and density of vegetative cover on the watershed,
c) susceptibility of soils and valley alluvium to erosion,
d) the hydraulic efficiency of the drainage system, and
e) the aerial extent and density of vegetative cover on the watershed.

All eroded material does not enter a stream system. Some detached particles travel for a short distance and get deposited for want of sufficient overland or channel flow. Some may travel downstream and get lodged in the vegetation on the banks. Some may be carried downstream only to be deposited in the plains. Thus, all the sediment produced by a watershed may not be delivered at a downstream point. Measurements show that as little as 5 % and as much as 100 % of the materials eroded in some watersheds may be delivered to a downstream point. The total amount of eroded material that passes through a section, such as a gauging site, is the *sediment yield* at that point. The quantity of sediment delivered to a reservoir depends on the rate of gross erosion in the watershed and the ability of the stream system to transport eroded material to the reservoir. The yield per unit area is termed as *specific sediment yield*. The sediment that enters into a reservoir is the sediment yield of the catchment and not the total eroded matter. The sediment production rate is worked out by dividing the annual producted by the watershed area and is normally expressed as tonnes per unit drainage area per year.

As a general rule, the average rate of sediment production decreases as the size of the drainage area increases, just as runoff per unit area decreases with the increase of drainage area. The main cause is that larger the watershed, the greater the opportunity for deposition between the points of origin and the reservoir. Besides, the larger the watershed, the lesser is the variation between the rates. Generally very high and very low production of sediments per unit area are found in small watersheds. This is because a very small watershed may be entirely forested as well as entirely cultivated. The watershed with forests may produce small amounts of sediment while the cultivated watersheds produce very high amounts. In larger watersheds, land use tends towards greater uniformity with less variation between rates of sediment production.

The fraction of eroded sediment that is delivered at a point is known as the *sediment delivery ratio.* Higher sediment-delivery ratio is associated with smaller catchments. As one moves upstream, the basin area decreases and the topographic factors that promote sediment delivery become more intensified resulting in a higher sediment delivery ratio. The sediment delivery ratio (D_R) is mathematically expressed as

$$D_R = S_y/E_g \tag{12.9}$$

where S_y is the sediment yield and E_g is the gross erosion. In general, the sediment discharged to large rivers is usually less than one-fourth of that eroded. ASCE (1975) have tabulated sediment delivery ratio and drainage area which show a near straight line relation when plotted on a semi-log graph (Fig. 12.5). The equation of the best-fit line is:

$$D^R = 5.07 \ln A + 36.86 \tag{12.10}$$

where A is catchment area (km^2).

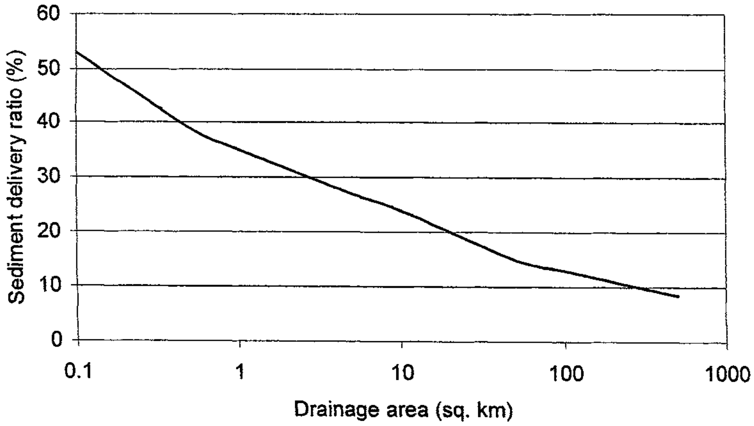

Fig. 12.5 Variation of sediment delivery ratio with drainage area

Besides area, catchment physiography, transport system, texture of eroded material influence this ratio. The sediment delivery ratio is small for big catchments with mild slopes and is large for small catchments with steep slopes. The effect of slope can be expressed through *relief length ratio* (*R*) as:

$$R = h/L \tag{12.11}$$

where *h* is the relief of watershed between the minimum and the maximum elevation (m), and *L* is the maximum length of watershed (m). The relief length ratio can be determined from topographic maps. Many workers have developed regression equations relating sediment yield with factors to account for climate and vegetative growth, topography, and soil properties (See Singh, 1992).

12.3.1 Methods of Sediment Yield Determination

A huge amount of research effort has been spent on understanding and modeling the soil erosion process. Many scientific studies have been conducted on experimental watersheds to assess the effect of land use on soil loss. The land uses which have been studied include forests, grasslands, agricultural lands, fallow lands, ravine lands, bare lands, and horticultural lands.

Approaches ranging from empirical methods to detailed physical model have been used to predict reservoir sedimentation. The choice of a prediction method largely depends on the objectives of the study; it may vary in different stages (planning, feasibility study, design and operation). As such, there is no best method that can be used for all the river basins. Nowadays, mathematical modelling has become a widely used tool. These methods to determine sediment yield are briefly summarised in what follows.

12.3.2 Comparison with Nearby Watersheds and Reservoirs

If sufficient data about the watershed in question are not available, the annual sediment yield rate (per unit of drainage area) of another watershed of similar characteristics (physiography, climatology) can form an initial estimate for the project watershed. Field inspections of the watershed will disclose the main sources of sediment, such as sheet erosion, gullying, flood erosion due to deforestation, and stream channel erosion.

If there is a reservoir in a nearby watershed and its sediment-deposition data are available for many years, the sediment yield rate of that basin can be estimated by considering the trap efficiency of the reservoir. However, the results of nearby basins are comparable only if the catchment properties, size, and the hydrometeorological characteristics are identical. It may be necessary to adjust the yield rate to account for variations in the drainage characteristics.

The data obtained from surveys of the reservoirs in the region can be plotted against catchment area and a regression relation can be developed. The data can also be used to prepare sediment yield maps. Fig. 12.6 shows such a map for India. However, such maps should be used with caution because while preparing such maps, a large area with wide variations in factors that affect soil erosion is divided into a smaller number of

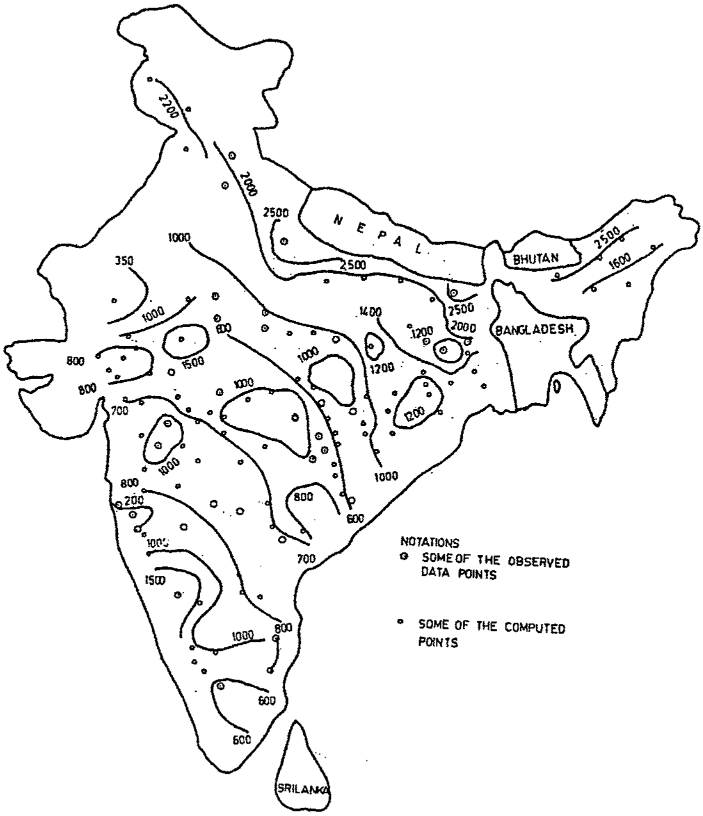

Fig. 12.6 Iso-erosion rate (tonnes/km^2/yr) map for India [Source: Garde (1995)].

supposedly homogenous areas. Nonetheless, these maps are useful when there is very little or no data about the basin in question.

12.3.3 Stream Gaging

This method involves setting up a stream gaging site and carrying out sediment measurement along with gauge and discharge observations. This aspect is discussed in Chapter 2. It is important to have long term sediment data because sediment load varies widely from season to season.

The sediment inflow into the reservoir including the bed load, and the outflow from it need to be measured at all significant points of entry and exit. The difference gives the quantity deposited during the period of analysis. The points of inflow measurement should be sufficiently close to the reservoir periphery. Care must be taken while outflow sampling because it should be done before the flow meets an erodable channel downstream.

12.3.4 Mathematical Modelling of Reservoir Sedimentation

The equilibrium sediment transport model is adopted in most mathematical models. In the equilibrium sediment transport model, the difference between the instantaneous sediment concentration and sediment carrying capacity is neglected. If the this difference is taken into account, the approach belongs to the non-equilibrium sediment transport model. For coarse sediment particles, equilibrium sediment transport model can be used, but for very fine sediment particles, non-equilibrium model better reflects the reality. Unit sediment graphs, which follow the same concept as the unit hydrograph, are explained by Singh (1992).

Mathematical models of sediment transport and deposition solve a system of governing equations. These are: the equation of continuity for water, momentum equation, equation of continuity for sediment, sediment transport law (e.g., a power law), and resistance law (Manning's or Chezy's law). The various mathematical models basically differ in the use of sediment transport and resistance law, the nature and type of terms that are included in momentum equation, and methods of solution of the equations. Before discussing a few models, the universal soil loss equation and its variants are discussed. This is perhaps the most widely used method of estimating soil erosion.

12.3.5 Universal Soil Loss Equation (USLE)

This is an empirical equation which was developed in the 1960s by Wischmeier and Smith (1965) to predict long-term interrill and rill erosion rates based on analysis of data of a large number of experimental plots in the United States. This equation has, however, been used world wide in varying climatic, geologic and landuse scenarios. Interrill erosion is a process of soil detachment by the impact of raindrops, transport by shallow sheet flow, and delivery to rill channels. Rill erosion is the erosion of sediment by concentrated flow. Rills carry flow from interrill areas as well as the rain that directly falls on them. The USLE is written as:

$$A = R*K*L*S*C*P \tag{12.12}$$

where A is the soil loss per unit area, expressed in the units of K and period selected for R; R is the rainfall and runoff erosivity factor; K is the soil erodibility factor; L is the slope length factor; S is the slope steepness factor; C is the crop management factor; and P is the support practice factor. The word 'universal' is used probably because the equation considers the five principle factors which influence soil loss: K, R, LS, C, and P.

In the 1980s, the USLE was revised to incorporate additional research and technology developed. This resulted in a new equation called the Revised USLE or RUSLE (Renard et al., 1994). RUSLE maintains the basic structure of USLE but the algorithms used to calculate the individual factors have been changed significantly. The estimation of the factors has been computerised to assist their determination.

A brief description of the various factors of equation (12.12) follows.

R-Factor: The *rainfall-runoff erosivity factor* in RUSLE is calculated as the product of storm kinetic energy times the maximum 30-minute storm depth and summed for all storms in a year. The R-factor represents the input that drives the sheet and rill erosion processes. The differences in R values represent differences in erosivity of the climate. Part of the R-factor calculation involves a seasonal distribution to permit weighting of the soil erodibility value, K, and the cover-management factor, C. To facilitate these calculations, climate data files have been developed (called a city code) for climatically homogeneous areas.

K-Factor: This *soil erodibility factor* is a measure of the inherent erodibility of a given soil under the standard condition of the unit USLE plot maintained in continuous fallow. Soils with high sand and clay contents have lower values and soils with high silt contents have higher values. In RUSLE, K also varies seasonally which is a major change over the USLE procedure. Experimental data show that K is not constant but varies with season, being highest in early spring and lowest in mid-fall or when the soil is frozen.

L- and S-Factor: The estimation of the *length-slope factor* is somewhat subjective, because the choice of a slope length involves judgment; different users choose different slope lengths for similar situations. RUSLE includes improved guides for choosing the slope length values to give greater consistency among users. Regarding the L-factor, the soil loss is less sensitive to the slope length than to any other USLE factor. For typical slope conditions, a 10 % error in the slope length measurement results in a 5 % error in the computed soil loss. RUSLE uses four separate slope length relationships. Three are functions of slope steepness as in USLE, and of the susceptibility of the soil to rill erosion relative to interrill erosion. For a given slope and its length, the LS factor can be computed as:

$$LS = (\lambda/72.6)^m(65.41\sin^2\theta + 4.56\sin\theta + 0.065) \qquad (12.13)$$

where λ is the slope length in feet; θ is the angle of slope; and $m = 0.5$ if the percent slope is 5 or more, = 0.4 on slopes of 3.5 to 4.5 %, = 0.3 on slopes of 1 to 3%, and 0.2 on uniform gradients of less than 1%. Soil loss is much more sensitive to changes in slope steepness than to changes in slope length. Thus, special attention should be given to obtaining good estimates of slope steepness. RUSLE has a more nearly linear slope steepness relationship and also provides a slope steepness relationship for short slopes subject primarily to interrill erosion.

C-Factor: The *vegetative cover factor* is perhaps the most important RUSLE factor because it represents conditions that can most easily be managed to reduce erosion. The values of C can vary from near zero for a very well protected soil to 1.5 for a finely tilled, ridged surface that produces much runoff and leaves the soil highly susceptible to rill erosion.

Values of C are a weighted average of the soil loss ratios that represent the soil loss for a given condition at a given time, to that of the unit plot (a unit plot is one maintained in clean-tilled fallow). Thus, soil loss ratios vary during the year as soil and cover conditions change. To compute C, soil loss ratios (SLR) are weighted according to the distribution of erosivity during a year. In RUSLE, a subfactor method is used to compute SLRs as a function of four subfactors given as

$$C = PLU \, . \, CC \, . \, SC \, . \, SR \tag{12.14}$$

where *PLU* is the prior land use, *CC* is the crop canopy, *SC* is the surface or ground cover (including erosion pavement) and *SR* is the surface roughness.

P – Factor: The *erosion control practice factor* mainly represents how surface conditions affect flow paths and flow hydraulics. For example, with contouring, runoff flows around the slope in channels formed by tillage. The grade and flow velocities could be much lower than in up-and-down hill flow paths. Of all the factors, the values for the P-factor are the least reliable. There are many interacting variables that determine the effect of contouring. The size of storm, antecedent soil water, and tillage are some of these variables that interact in such a way that a contouring factor may vary widely from storm to storm and field to field; these interactions have made it difficult to document in the limited number of field studies dealing with contouring. Likewise, identifying these subtle characteristics in the field is difficult when applying RUSLE. Thus, the P-factor values represent broad, general effects of such practices as contouring.

The RUSLE P-factors are treated as the product of sub-factors computed based on practices applied to the landscape. In RUSLE, extensive data (both field and model) have been analyzed to reevaluate the effect of contouring. The results have been interpreted to give factor values for contouring as a function of ridge height, furrow grade, and climatic erosivity. New P-factor values for the effect of terracing account for grade along the terrace while a broader array of strip cropping conditions are considered in RUSLE. Finally, P-factors in RUSLE have been developed to reflect conservation practices on range lands. The practices require estimates of surface roughness and runoff reduction.

The steps in estimation of soil loss using USLE are given in Fig. 12.7. Although the universal soil loss equation has been widely applied all over the world and for catchments of widely varying sizes, the results may be erroneous unless the model is applied with care and the parameters are adapted to local conditions. Note that no physical processes are simulated in this model and the antecedent conditions are not considered. Therefore, the model is not well suited to predict soil loss from individual events. Further, this model was developed using the data of soils on mild slopes and hence its application to soils on steep slopes should be with caution.

Example 12.2: A catchment is located in foothills of Himalayas and has clayey soil with $K = 0.33$. The verage slope is 2.41% and the slope length is 393 ft (120m). It has sub-humid temperate climate with annual rainfall of 1705 mm, rainfall-runoff factor about 350, crop-management factor $C = 0.3$, and $P = 0.2$. Calculate the average annual soil erosion.

Solution: For a slope length of 393 ft, and $\theta = 2.17°$, $m = 0.3$, and. Using eq. (12.12), $LS = 0.35$. Hence, the average annual soil loss per unit catchment area is:

$A = 345*0.33*0.35*0.30*0.20 = 2.39$ t/ha/year.

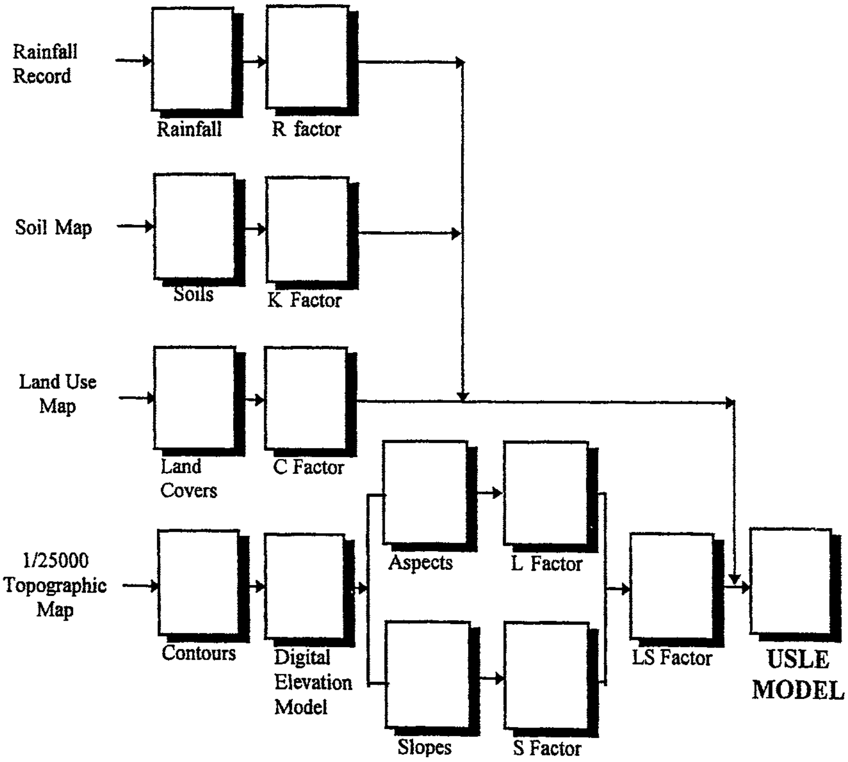

Fig. 12.7 Steps in estimation of soil loss using USLE [Source: Harmancioglu et al., 1998].

12.3.6 HEC-6 Model

The HEC-6 model was developed by Thomas (1977) at the Hydrologic Engineering Centre of the U. S. Army Corps of Engineers and this description is mainly based on the users' manual for the model software. HEC-6 is a one-dimensional steady flow model designed to analyse scour and deposition by modelling the interaction between the water-sediment mixture, sediment material forming the stream's boundary, and the hydraulics of flow. It simulates the ability of the stream to transport sediment and considers the full range of conditions embodied in Einstein's bed load function plus silt and clay transport and deposition, armoring and the destruction of the armor layer. The model subdivides channel cross-section into two parts -- a part which has a movable bed, and that which does not; the boundary between these parts remains fixed. The entire movable bed part of the cross section is moved vertically up and down. The model does not account for density currents and secondary currents.

The reservoir deposition can be analysed to determine both the volume and location. The degradation of the streambed downstream from a dam can also be determined. Long term trends of scour or deposition in a stream channel, for instance those that would result from modifying frequency and duration of the water discharge or stage or from encroaching of flood plains, can be simulated. The HEC-6 program can be used to assess the influence that dredging has on the rate of deposition, scour during floods, and the impact of a reservoir, etc. on the water surface profile and the water depth.

The basis for simulating the movable bed is the solution of the continuity equation for sediment material (the Exner equation):

$$\frac{\partial G}{\partial x} + B_0 \frac{\partial Y_S}{\partial (DD)} = 0 \qquad (12.15)$$

where G is the sediment load in m^3/day, DD is the duration of time step, Y_S is the depth of sediment deposit in the control volume, x is the distance along the channel, and B_0 is the width of deposit (movable bed). This equation is expressed in finite difference form for point P using the notations shown in Fig. 12.8.

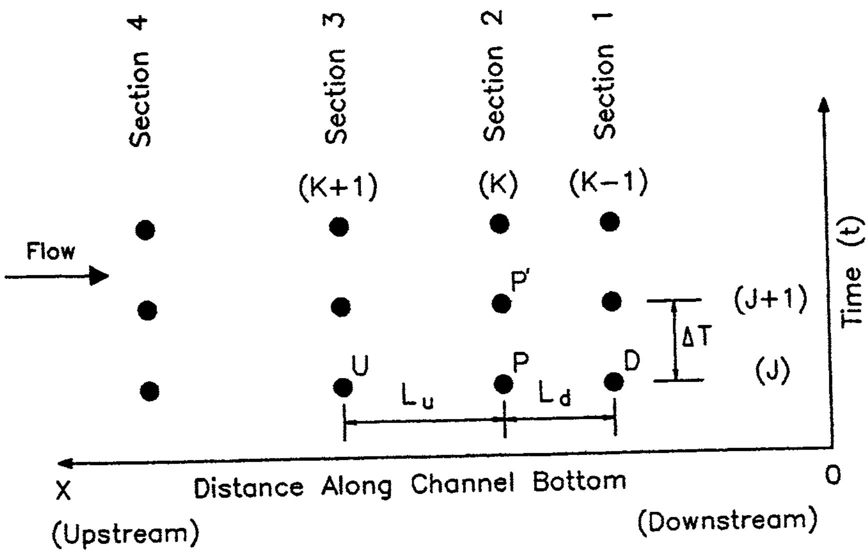

Fig. 12.8 Computation grid of HEC-6 [Source: HEC (1991)].

$$\frac{G_u - G_d}{0.5(L_d + L_u)} + \frac{B_{sp}(Y'_{sp} - Y_{sp})}{DD} = 0 \qquad (12.16)$$

$$Y'_{sp} = Y_{sp} - \frac{DD}{0.5 B_{sp}} \cdot \frac{G_u - G_d}{L_d + L_u} = 0 \qquad (12.17)$$

where B_{sp} is the width of the movable bed at point P, G_u and G_d are sediment loads at the upstream and downstream cross sections, respectively, L_u and L_d are the upstream and downstream reach lengths, respectively, Y_{sp} and Y'_{sp} are the depths of sediment before and after time step, respectively. The initial depth of bed material at point P defines the initial values of Y_{sp}. The sediment load G_u is the amount of sediment, by grain size, entering the control volume from the upstream control volume. For the upstream-most reach, this is the inflowing boundary condition provided by the user. The sediment leaving the control volume, G_d, becomes the G_u for the next downstream control volume.

The sediment load, G_d, is calculated from the transport capacity at point P, the sediment inflow, and availability of material in the bed and armoring. The difference between G_d and G_u is the amount of material deposited or scoured in the reach between points D and U during the time step, and is converted to a change the in bed elevation using eq. (12.17).

The time step of fraction of a day is typical for large water discharges; it may be appropriate to use several days or even months for low flows. It is important that each time interval be short enough so that changes in bed elevation due to scour or deposition during that time interval do not significantly influence the transport capacity by the end of the time interval. Regarding the amount of change in bed elevation that can be tolerated in one time step, a value equal to 0.3m or 10% of the water depths whichever is less, gives good results. The gradation of the bed material is recalculated during the time interval because the amount of material transported is very sensitive to the gradation of the bed material.

The basic hydraulic parameters needed to calculate sediment transport capacity are velocity, depth, width and slope -- all of which come from water surface profile calculations. The one-dimensional energy equation, shown below, is solved using the standard step method, and the above hydraulic parameters are calculated at each cross section (see Fig. 12.9):

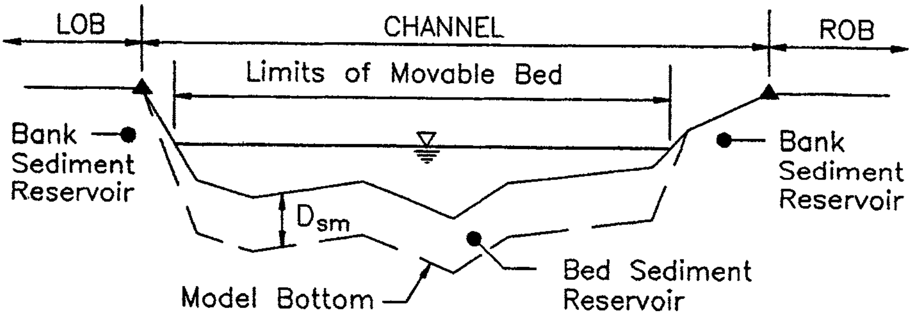

Fig. 12.9 Sediment material in the streambed [Source: HEC (1991)].

$$WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \tag{12.18}$$

$$h_e = h_f + h_0 \tag{12.19}$$

The energy loss term, h_e, in eq. (12.18) is composed of friction loss, h_f, and form losses, h_0. Only the contraction and expansion losses are considered in the form loss term.

Further details of the model are available in Thomas (1977) and HEC (1991).

12.3.7 The WEPP Model

The Water Erosion and Prediction Project (WEPP) model was developed as a cooperative effort of four organisations with the leading role for the U.S. Department of Agriculture. The main aim was to employ the current knowledge to develop a model as an alternative to USLE. The model carries out a simulation of the physical processes that cover erosion. There are three versions of the model: mountain slope, watershed, and grid. The concepts of stochastic weather generation, infiltration theory, hydrology, hydraulics, soil physics, plant science, and erosion mechanism have been used in this model. The mountain slope model simulates the erosion process from different types of land uses and treatment. The watershed version is a catchment model which includes the slope model and estimates the sediment delivery to channels. The sediment that is loaded is routed to the catchment outlet by simulating the process of erosion and transportation. The grid version is used for large areas which need not be within one watershed. The model uses a daily time step and simulates the process of plant growth, soil properties and hydrologic processes. A conceptual representation of a hillslope and a watershed for application of WEPP are shown in Fig. 12.10 and 12.11.

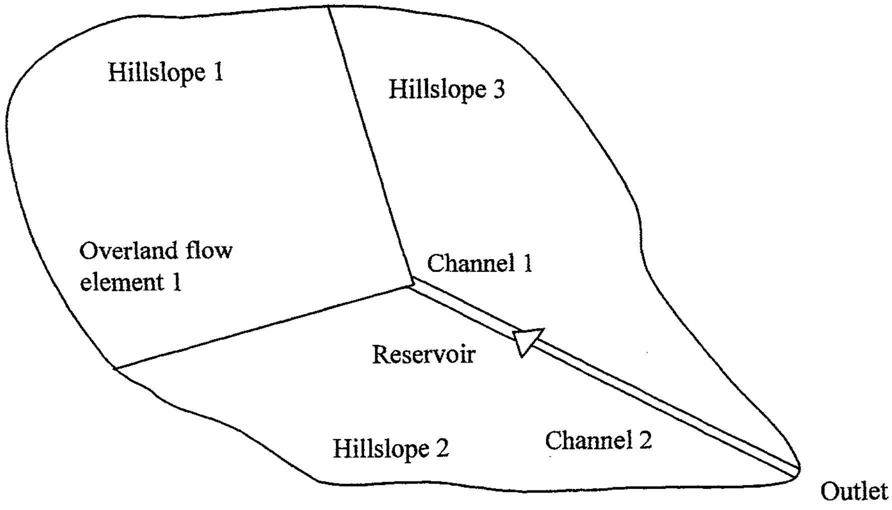

Fig. 12.10 Representation of watershed in WEPP erosion model.

The WEPP watershed model is made up of four major components: hillslope, channel, impoundment, and irrigation. The hillslope component is the WEPP hillslope model which calculates erosion and deposition on rill and interrill flow areas. It can consider processes, such as infiltration, sediment transport and deposition, evaporation, transpiration, snow melt, residue and canopy effects on soil detachment, and contour effects. It is able to account for spatial and temporal variations in topography, surface roughness, soil properties, crops, and landuse on hillslopes. The channel component calculates erosion and deposition within concentrated flow areas which can be represented as permanent channels or ephemeral gullies. The impoundment component calculates deposition of sediment within terrace impoundments and stock tanks. The irrigation component calculates erosion and deposition on border irrigation areas.

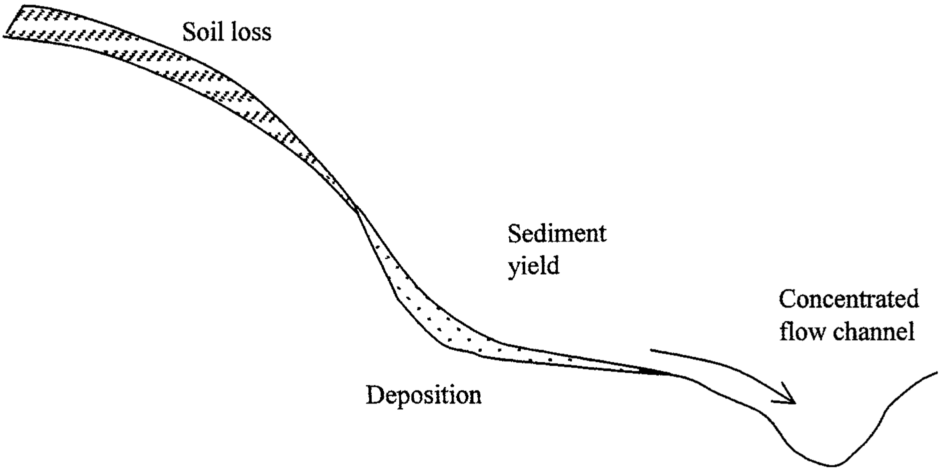

Fig. 12.11 Representation of hillslope in WEPP erosion model.

A watershed must be represented by at least one hillslope element. In the WEPP watershed model, hillslope elements can contain up to 10 overland flow sub-elements which may represent changes in cropping patterns (strip cropping), soil variation in the downslope direction, different land use patterns, or changes in grazing intensities. A hillslope element can drain into a channel either at the headwaters or laterally, or into an impoundment. A channel element can receive water and sediment input from hillslope elements, upstream channel elements (up to three channel elements), or an impoundment. An impoundment element can receive input from hillslope or channel elements.

Specifically the model considers three erosion processes: detachment, transportation and deposition. The channel erosion and grid erosion is modelled using hydraulic concepts. In case there is a reservoir within the catchment, the same can also be considered. A brief description of the model is given here. For details, reference may be made to Lane and Nearing (1989). The WEPP erosion model uses a steady-state sediment continuity equation to describe the downslope movement of suspended sediment in a rill:

$$dG/dx = D_f + D_i \tag{12.20}$$

where x (m) represents the distance downslope, G (kg/s/m) is the sediment load, D_i (kg/s/m^2) is the lateral sediment flow from the interrill areas, and D_f (kg/s/m^2) is the rill erosion or deposition rate. Interrill sediment delivery, and D_i, is considered to be independent of x. Rill erosion, D_f, is positive for detachment and negative for deposition.

Interrill erosion is conceptualized as a process of sediment delivery to rills, whereby the interrill sediment is either carried off the hillslope by the flow in the rill or deposited in the rill. Sediment delivery from the interrill areas is considered to be proportional to the square of rainfall intensity, with the constant of proportionality being the interrill erodibility parameter. The function for interrill sediment delivery also includes terms to account for ground and canopy cover effects, which are discussed below.

The net soil detachment in rills is calculated for the case when hydraulic shear stress exceeds the critical shear stress of the soil and when sediment load is less than the sediment transport capacity. For the case of rill detachment,

$$D_f = D_c\,(1 - G/T_c) \tag{12.21}$$

where D_c is the detachment capacity by flow and T_c (kg/s/m) is the sediment transport capacity in the rill. Rill detachment is considered to be zero when the hydraulic shear stress is less than critical shear strength of the soil. The net deposition is computed when the sediment load, G, is greater than the sediment transport capacity, T_c. For the case of deposition

$$D_f = (V_f / q)\,(T_c - G) \tag{12.22}$$

where V_f (m/s) is the effective fall velocity for the sediment, and q (m^2/s) is the discharge per unit width. The overland flow hydrograph is developed by assuming broad, uniform sheet flow. Once the unsteady flow calculations are made to get the runoff peak rate and duration, quasi–steady state flow is assumed at the peak rate and is partitioned into broad sheet flow for interrill erosion and concentrated flow for rill erosion. The kinematic wave equations for one-dimensional overland flow are:

$$\partial h/\partial t + \partial q/\partial x = r - f = v \tag{12.23}$$

$$q = \alpha\, h^{3/2} \tag{12.24}$$

where h is the local flow depth (m); t is the time (s); q is the discharge per unit width (m^2/s); x is the distance down the plane (m); r is the rainfall intensity (m/s); f is the infiltration rate (m/s); v is excess rainfall rate (m/s), and α is the depth –discharge coefficient (m$^{0.5}$/s).

Prediction of the effects of land use and management practices on erosion control are perhaps the most important part of an erosion prediction tool if the purpose is to plan land and farm management systems to control erosion. Farmers can control soil loss through residue management and tillage practices. In the WEPP erosion model, the interrill sediment delivery is adjusted to account for the effects of ground cover, dead roots, live roots, and canopy cover.

The parameters used by the hydrology and erosion components of the model that must be input by the user include soil conditions for the day of the rainfall event, crop canopy, surface residue, days since last disturbance, surface random roughness, oriented roughness, etc. WEPP model may also be executed in a single-storm mode, although it is very effective when used as a continuous simulation model. Surface residue, for example, plays an important role in terms of predicting the amount of soil lost during a given rainfall event. An erosion model may use a plant growth and residue decay model to estimate the amount of crop residue present on the soil surface for each day through the year.

The output of the continuous simulation model represents the time-integrated estimate of erosion. In nature as well as in the model predictions, a large percentage of erosion occurs due to a small percentage of rainfall events. The model simulates erosion for some number of years and sums the total soil loss over those years for each point on the hillslope to obtain the average annual values of erosion along the hillslope. The model calculates both detachment and deposition. It predicts where deposition begins and/or ends on a hillslope, which may vary from storm to storm. Certain points on the hillslope may experience detachment during some rainfall events and deposition during other events. In this case, the output represents an average of the erosion events.

The WEPP landscape profile version model requires four input data files: a soil file, a slope profile file, a crop management file, and a climate file. The model requires huge data on various variables for a good implementation; the required climatic data includes rainfall, its peak and duration, temperature data, wind velocity and direction, solar radiation, snowfall and snowmelt. The user must have file building tools and access to appropriate soil, tillage implement, plant, and climate databases in order to build the four data files. Since this is a tedious task, expert systems have been developed for the assistance of a user. The theory of the model has been described in detail by Finkner et al. (1989) and USDA (1989).

12.4 RESERVOIR SURVEYS

Sediments accumulated in an existing reservoir can be determined by periodically running a sediment survey of the reservoir. It is a direct measurement procedure to assess the volume of deposit along with its pattern in the reservoirs. Other valuable information gathered in these surveys includes how the sediment deposits are distributed in the reservoir. Sediment data collected during the surveys are analyzed to determine the specific weights of the deposits, their grain size distribution, sediment accumulation rates, and trap efficiency. The recent advances in technology have considerable reduced the efforts in reservoir surveys and analysis of data. Note that the maximum information about the reservoir bed profile will be obtained when the reservoir water level is high.

The frequency of surveying the reservoirs depends on the sediment accumulation rate. Reservoirs that have high accumulation rates are surveyed more often than those with lower rates. The cost of running a survey also plays a critical part in deciding their frequency. Generally the reservoirs are surveyed every 3 to 10 years. Special circumstances may necessitate a change in the established schedule. For example, a reservoir might be surveyed after a major flood that has carried heavy sediment load in the reservoir. A survey may also be run following the closure of a major dam upstream in the same catchment since the reduction in the free drainage area leads to a reduction in the sediment accumulation rate of the downstream reservoir. The volume of the sediment that has accumulated in a reservoir is computed by subtracting the revised capacity from the original capacity at a reference reservoir elevation (usually the FRL). Since this is the difference of two large numbers, an error, even by a few percentage in either of the two numbers will significantly influence the results.

The advantages of reservoir surveys are:

1. The reservoir survey can be less costly than continuous sediment measurement at several locations in the catchment.
2. The accuracy of these surveys is usually very high, particularly if advanced equipment are used.
3. It is possible to estimate the total sediment load (bed and suspended load) being carried by the river.
4. The survey can be carried out at any convenient time to get the total sedimentation after the last survey.
5. The time required for a survey can be considerably shortened with the use of advanced equipment.

There are some limitations of the reservoir sedimentation survey.

1. The unit weight of sediment is required to estimate sediment yield. This weight is estimated using samples from selected locations within the reservoir. Usually only limited samples are taken and thus spatial variation may not be properly estimated. Furthermore, due to compaction, the weight changes with time and this may introduce errors in the results.
2. Such surveys do not provide any information about the variation of sediment yield with time and give only the total sediments accumulated since the last survey. This information can only be obtained by gauging.
3. This method does not provide sub-catchment wise sediment yield which can be obtained by sediment sampling of different streams.
4. This approach is not very effective where sedimentation is small, as the errors of measurement may mask the true sedimentation rates.
5. To find the total sediment inflow, sediment outflow data is also needed.

It is essential to have accurate map of the reservoir at an appropriate scale, e.g., 1:10,000 scale prior to commencement of the hydrographic survey. The important reservoir features, such as the FRL along the periphery, position of dam, outlets, location of inflowing streams etc. should be precisely marked on the map. Other topographic details, such as position of islands, permanent structures, bridges, roads, villages, etc., are also recorded. It is also necessary to mark control points in the study reach prior to commencement of the survey. Horizontal and vertical control points are fixed at a suitable interval (say 5 km in horizontal and a few meters in vertical) on the circumference of the reservoir. After fixing the control points in the outer boundary of the study reach, x-sections are planned at a suitable interval depending on the reservoir size.

The contour and range methods are two basic techniques of the reservoir survey. In some situations, a combination of both is used. The selection of a method depends on the quantity and distribution of sediment indicated by field inspections, shape of the reservoir, purpose of the survey, and desired accuracy.

12.4.1 Contour Survey Method

This is a very accurate approach to obtain the complete profile of the reservoir bed. The contour method of survey is generally helpful for all types of reservoir shapes. The capacity of the reservoir at the time of survey is computed, based on depth measurements over the reservoir bed. The general methods of contour survey are grid contouring, radial contouring, and circular contouring.

Using the level data gathered during the survey, a contour map of the reservoir is prepared. By planimetering the successive areas enclosed by the contours starting from the lowest contour, a table of elevation and submergence area is prepared. The storage capacity between successive elevations (ΔV) can be worked out by the Prismoidal formula:

$$\Delta V = \Delta H\,(A_1 + A_2 + \sqrt{A_1 * A_2})\,/3 \qquad (12.25)$$

where ΔH is the elevation difference between adjacent contours, and A_1 and A_2 are the areas enclosed by the contours. The cumulative value of the capacity is obtained by starting from the lowest elevation and adding the successive values and the elevation-capacity table is obtained. The difference in the capacity between two surveys indicates the loss of capacity due to sediment deposition during the intervening period.

12.4.2 Range Survey Method

This method is widely used and enables estimation of sediment accumulation with minimum of field data. The range method is more suitable for reservoirs with relatively straight reaches. This method of capacity survey consists of levelling or sounding along a fixed set of ranges or cross-section lines across the reservoir which may be re-surveyed at a pre-determined interval later on. The survey data forms the basis for computation of volume contents of the reservoirs. A suitable combination of range and contour survey may also be justified in some cases.

The object is to compute the end areas at different cross sections and carry out volumetric computation on that basis. Nowadays, many advanced tools are available to help in the surveys. The position of the surveys can be accurately determined through the Global Positioning System (GPS) described below. The range layout can be easily planned using software packages; many such commercial packages are available.

A typical pattern of range locations is shown in Fig. 12.12. The spacing between range lines need not be constant; it should be closer in the area of special interest or the zone where higher sedimentation is expected. The range lines should be perpendicular to the reservoir axis. The ranges should be set up across the mouth of each major arm of the reservoir as well as each major inflowing channel. The extreme end where sediment deposition begins should also be covered. It has been recommended that the minimum of three ranges should be marked. Morris and Fan (1998) have suggested the following formula as a rough guide to decide the number of range lines:

$$\text{Number of range lines} = 2.942\ A^{0.3652} \qquad (12.26)$$

where A is the reservoir surface area in ha. A number of methods are available to process the data from range surveys. The methods used in contour surveys can also be applied.

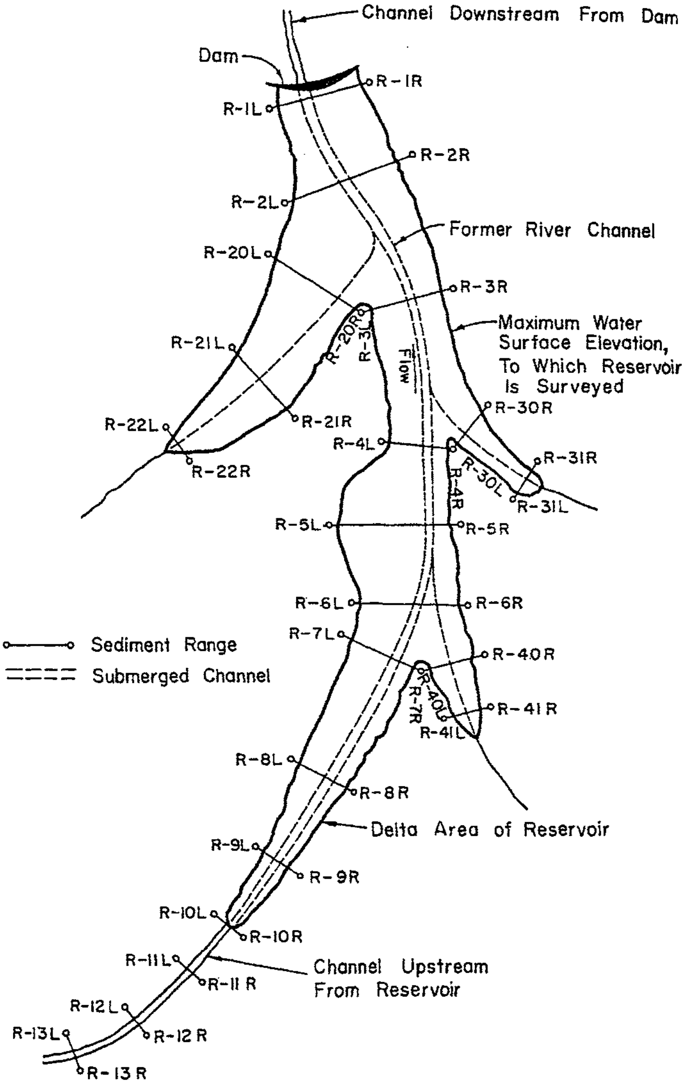

Fig. 12.12 A layout of range lines for reservoir surveys [Source: Borland (1971)].

12.4.3 Instruments for Reservoir Survey

Hydrographic surveys of reservoirs can be conducted either by a conventional method with plane table, sextant, range finders and sounding pole or by using automated computerised technology comprising of positioning system, depth measuring system, and data acquisition and analysis system. The equipment required to run a survey consist of land surveying instruments, sonic sounders, boats, and a variety of auxiliary equipment. Two-way radios are needed when it is necessary to maintain communication between shore and boat parties. Currently, portable survey equipment and measurement devices are available which can measure and store data about the x, y, and z coordinates of the reservoir bottom in real-time on a computer media for subsequent processing. Software to generate contour maps or range profiles including 3-D maps from these data are widely available.

Global Positioning System

The United States Department of Defence conceived and installed a radionavigation "ranging" or "distance measurement" system using a constellation of satellites. This system was named as Global Positioning System (GPS). It is a satellite surveying system to provide, using the known positions of satellites in space, precise location of unknown positions on land, sea, and in the air. GPS reached full operational capability in July 1995.

GPS consists of three segments: space, control, and user.

The Space Segment consists of 24 operational satellites in six circular orbits 20,200 km (10,900 NM) above the earth at an inclination angle of 55 degrees with a 12-hour period. The satellites are spaced in orbit so that at any time a minimum of 6 satellites will be in view to users anywhere in the world. The satellites continuously broadcast position and time data to users throughout the world.

The Control Segment consists of a master control station in Colorado Springs, with five monitor stations and three ground antennas located throughout the world. The monitor stations track all GPS satellites in view and collect ranging information from the satellite broadcasts. The information collected from each of the satellites is sent back to the master control station, which computes extremely precise satellite orbits. The information is then formatted into updated navigation messages for each satellite.

The User Segment consists of the receivers, processors, and antennas that allow land, sea, or airborne operators to receive the GPS broadcasts. The user's receiver measures the time delay for the signal to reach the receiver, which is the direct measure of the apparent range to the satellite and is used to compute their precise position, velocity and time.

GPS works on the principle of resection, i.e., locating the position of the surveyor with reference to known positions in space. The known positions refer to those of 24 satellites that continuously transmit microwave radio signals on two frequencies. GPS signals contain 3 key information, viz., satellite identification, precise time of the atomic clocks on the satellite, and orbital location of the satellite. To fix the position of the GPS receiver in space, the values of three unknowns, i.e., x, y, and z are to be determined in an earth-centered cartesian coordinate system. Additionally, the 4th unknown parameter is the time offset between precise atomic clocks on-board satellites and the clock on the GPS receiver. To solve for these 4 unknowns, ranging to at least 4 satellites is required.

GPS provides two levels of service -- a Standard Positioning Service (SPS) for general public use and an encoded Precise Positioning Service (PPS) primarily intended for use by the Department of Defense. SPS coverage is continuous and worldwide and the signal accuracy is intentionally degraded to protect the U.S. national security interests. This process, called Selective Availability (SA), controls the availability of the system's full capabilities. The SPS available to civilian users normally gives a 100-metre horizontal accuracy (95% of the time after SA). The vertical accuracy is about 1.5 times worse than horizontal, due to the satellite geometry.

Differential GPS (DGPS) is a means of correcting for some system errors by using the errors observed at a known location to correct the readings of a roving receiver. The basic concept is that the reference station "knows" its position, and determines the difference between that known position and the position as determined by a GPS receiver. This error measurement is then passed to the roving receiver which can adjust its indicated position to compensate.

The differential reference station computes the errors in the pseudorange measurements for each satellite in view separately, and broadcasts the error and other system status information. A differential beacon receiver receives and decodes this information, and sends it to the "differential ready" GPS receiver. The GPS receiver combines this information with the individual pseudorange measurements it makes, before calculating the position. DGPS eliminates the error introduced by SA and errors caused by variations in the ionosphere. DGPS systems can give coordinates within 3 meters, or so.

The use of GPS has significantly cut down the time to complete a survey. It eliminates the need for inter-visibility between receivers. There is no need for extra stations or line-of-sight visibility. Thus, control can be established in a short period of time even over a large area. Fog and rain do not affect data transmission and so little time is lost during inclement weather conditions. Work can be carried out at night also when atmospheric conditions are most favourable for GPS observations. While the application of GPS opens a whole new range of possibilities in survey planning and cost reduction, there are a few problems too. Signals from satellites are influenced by foliage and the system does not work well in the forested area. In urban areas with high rise buildings, the reflected signals lead to multi-path problems. It may also be noted that high solar radiation can cause disturbance to radio signals from satellites.

Depth Measuring Equipment

The main component of depth-measuring unit is an echo sounder. The echo sounder transmits the sound pulses downward into the water by a transducer. The echo reflected from the bed is also received by the echo sounder. The time interval between the emission of the sound pulse and its return as an echo is used to estimate the depth of the water. The echo sounder is capable of recording a continuous profile of the reservoir bed. Typically, the accuracy of the order of several cm can be obtained. Dual frequency echo sounder provides a higher accuracy, particularly in the cases where the reservoir bed is soft.

Sediment Samplers

Samples of the reservoir deposits are taken during surveys to determine specific weights and grain size distribution. A variety of samplers are used. Physical samples taken with core type samplers are analysed in the laboratory for gradation and specific unit weight. Radioactive probes can measure only in-situ wet bulk densities. The specific weight data are used to compute the mean specific weight of the sediment. The size distribution of the sample material is obtained from mechanical analyses. The size distribution data can be used to compute specific weights of sediment deposits. Generally, at least one sample is collected at each range. The total number of samples depends on the reservoir size, the type and texture of the inflowing sediments, and the location and number of inflowing rivers.

Software

Many computer software packages are available to process hydrographic survey data. A versatile software can interface a series of echo sounders and position fixing systems. The depth recorded by the echo sounder and its position determined by the GPS can be logged simultaneously by the software and the logged data is stored in the computer for post processing.

12.5 ASSESSMENT OF RESERVOIR SEDIMENTATION USING REMOTE SENSING

Remote sensing techniques, enabling acquisition and analysis of synoptic data over a broad spectral range, are an alternative to conventional methods of data acquisition and processing. The advantage of satellite data over conventional sampling procedures include repetitive coverage of a given area every few weeks, the availability of a synoptic view which is unobtainable by conventional methods, and almost instantaneous spatial data over the areas of interest. The remote sensing analysis is highly cost effective, and requires lesser time as compared to conventional methods. Spatial, spectral and temporal attributes of satellite data provide invaluable synoptic and timely information regarding the water spread area.

During the planning and design phases of a dam, contour maps of the reservoir area are carefully prepared. Due to deposition of sediments, the reservoir water spread area at various elevations goes on decreasing. A greater deposition of sediments at an elevation causes a greater decrease in this area. In the remote sensing approach, a series of imageries covering the range of reservoir water levels are obtained. These imageries are analysed to compute the number of contiguous reservoir water pixels in each. Multiplying the number of water pixels with the area of a pixel gives the water spread area of the reservoir at the time of satellite overpass.

Most reservoirs have annual drawdown and refill cycles. The actual water surface elevation in the reservoir at the time of satellite pass can be obtained from the dam authorities. An analysis of a series of imageries will give water spread of the reservoir at various elevations over the operation range. The reservoir capacity between two levels can be computed by the trapezoidal or prismoidal formula and the elevation-capacity table can be prepared. A comparison of this table with a previous table yields the capacity lost during the intervening period. The reservoir water spread area is determined by analysing the satellite imagery. The reduction in the water spread area with time helps in determining the sediment distribution and deposition pattern in a reservoir. This information can be used to quantify the rate of reservoir sedimentation.

It is important to note that the amount of sediments deposited below the lowest observed water level cannot be determined through remote sensing. Thus, it is not possible to estimate the actual sedimentation rate in the whole reservoir. It is only possible to calculate the sedimentation rate within the operational zone of the reservoir. However, to operate the reservoir, the capacity of the live storage zone and the pattern of sediment deposition within this zone is important.

12.5.1 Identification of Water Spread Area

The reflectance characteristics for vegetation, soil and water were presented in Fig. 3.5. In the visible region of the spectrum (0.4 - 0.7 μm), the transmittance of water is significant and the absorptance and reflectance are low; the reflectance scarcely rises above 5%. The absorptance of water rises rapidly in the near-infrared region (NIR) (0.77 - 0.86 μm) where both the reflectance and transmittance are low. The transmittance of visible radiation through water implies that if depth is shallow, the radiation is reflected by the bottom of the water body, transmitted back through the water, and detected by the sensor. In such cases, it may not be clear from the visible bands whether there is a thin water layer above the water surface. To resolve this, the image in the NIR band must be inspected as a submerged surface will not be detected in this portion because of the lack of transmittance. At NIR wavelengths, water apparently acts as a black body absorber and the boundary between the water and other surface features is quite prominent.

The reflectance from the wetland along the reservoir periphery may be quite similar to the reflectance from the adjacent shallow water. The reservoir water may be heavily laden with silt. It is also possible that a pixel at the soil-water interface may represent mixed conditions (some part water and other part soil). To differentiate water pixels from the adjacent wetland pixels, comparative analysis of the digital numbers in different bands is carried out. The behavior of the reflectance curves of water and soil is different from the blue band (0.53 - 0.59 μm) onwards. Beyond the blue band, with increase in wavelength, water reflectance curves show downward trend while soil curves show an upward trend. This characteristic can be used to differentiate the water pixels from the peripheral wetland pixels. The variation of soil reflectance with moisture content and the reflectance of water in different conditions is demonstrated in Figs. 12.13 and 12.14, respectively.

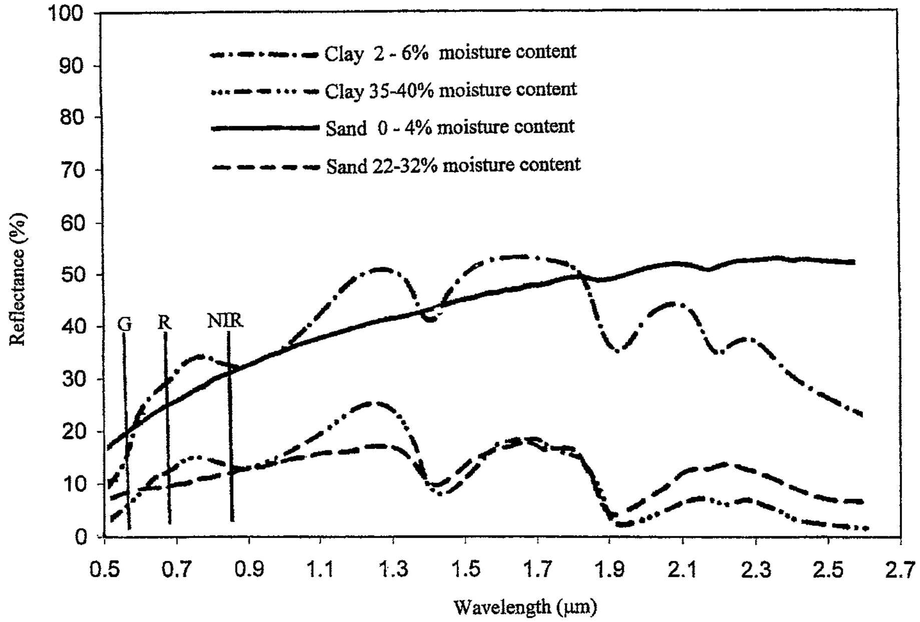

Fig. 12.13 Variation of soil reflectance with moisture content.

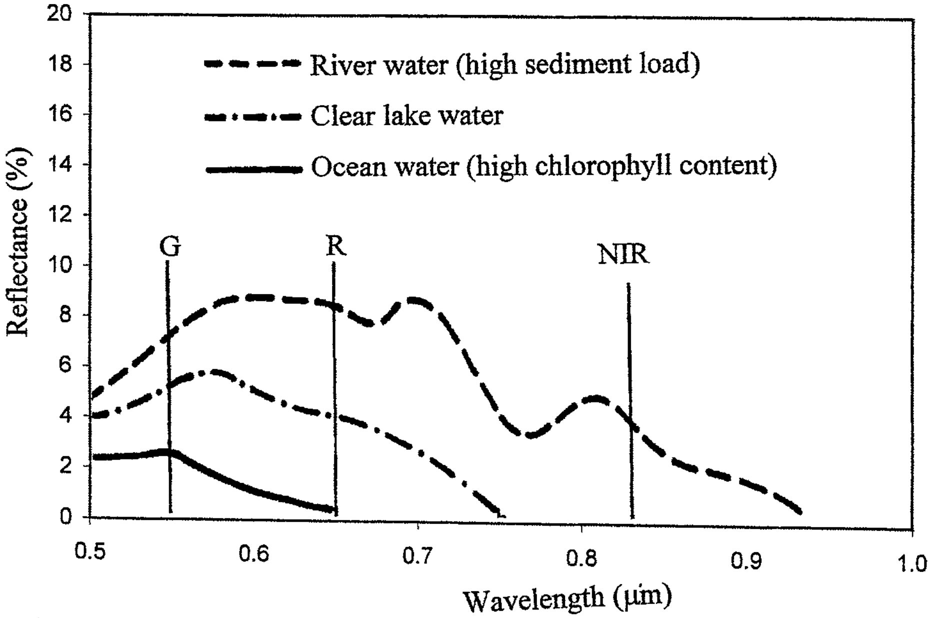

Fig. 12.14 Reflectance of water in different conditions.

12.5.2 Analysis of Imageries

The first step of analysis is to select the period whose data is to be used. It is a good idea to choose the year corresponding to the maximum variation in the elevation of the reservoir water level and consequently, the water spread area. Large water level variations will be noticed in a wet year followed by a dry year. Multi-spectral data are required for identification of water pixels and to differentiate the water pixels from the peripheral wetland pixels. It is necessary to ascertain that good quality cloud free satellite data are available. Besides, there might be some other reasons to select the period of analysis. It is also desirable to use high-resolution data for better results. The data of a number of satellites are available these days and a choice is usually made based on the frequency of satellite pass, spatial resolution, and cost considerations. These days, satellite data are mostly supplied on CD-ROM and Internet is being increasingly used for this purpose.

In digital image processing, the information of different spectral bands can be utilised. The information on the pixels covered by clouds can be extracted indirectly and noise in the data can be removed. A number of commercial software are available for digital image processing. The imagery needs to be imported in the software system before analysis can commence. While using the temporal satellite data of the same area, it is necessary to geo-reference the imageries acquired at different times. The geo-referenced imageries can be overlaid and changes in the water spread area can be detected. Geo-referencing also helps to manipulate the information below the clouds and under the noise pixels. One of the imageries which is sharp, clear, and cloud- and noise-free is chosen as the base (master). The imageries of other dates are considered slaves and geo-referenced with the master. Although the reservoir area may be covered in a small part of the scene, the full scene should be utilised for geo-referencing to improve accuracy. Clearly identifiable features, such as crossing of rivers, roads or lineaments, sharp turns in the rivers, bridges, the rock outcrops, are selected as control points. At least 10 control points should be selected. The geo-referencing statistics is examined and the points which generated large errors are edited/deleted or replaced by other points so as to obtain satisfactory results. Typically, the final error should be less than the size of a pixel.

Depending on the areal extent and spatial resolution, the file size of each scene can be very large. Since the area of interest is only the reservoir area, the reservoir water spread area and its surrounding can be extracted from the full scene before proceeding with analysis. This will result in less consumption of disk space, easy handling of files, and reduction in the analysis time. This will also reduce the efforts for display and editing files. The RS packages contain utilities for this purpose. For example, ERDAS/IMAGINE has a utility named *area of interest* (AOI). A polygon covering the reservoir spread area and some area adjacent to it is constructed. The data corresponding to this AOI polygon is saved in a new file.

Identification of Water Pixels

Many techniques are available to demarcate water pixels. Density slicing of the NIR band is one such method. Although most of the water pixels can be separated out by density slicing, it may fail under certain conditions. The sliced pixels may include some saturated soil pixels also since the reflectance value of the saturated soil is very low in the NIR band. Supervised classification is another approach. Although clearly distinguishable water pixels could be easily separated out by this technique, sometimes it is difficult to provide accurate training sets for peripheral pixels. Another approach is to apply a model that uses multispectral data and tests multiple conditions to ascertain whether a pixel represents water or not. Most modern packages have a provision to write algorithms to differentiate water pixels by processing the data of multiple bands.

After the water spread area is separated out, the resulting imagery can be compared with the NIR imagery and the standard FCC. There is a possibility of interpretation error because of the presence of mixed pixels along the periphery of the spread area. However, depending on the area covered by the water or soil in a mixed pixel, classification of some pixels as pure water and some as pure soil can mutually counterbalance the effect of misclassification to some extent. Note that the estimation of sedimentation by remote sensing is highly sensitive to determination of the water spread area. The data of high-resolution sensors helps to reduce the error in remote sensing analysis.

Accounting for Cloud Effect, Noise and Tails

If the imagery has clouds, their shadows might fall over the reservoir area and its periphery. It is necessary to determine whether the pixels occupied by clouds and shadows correspond to water or not. If clouds and shadows are present over the reservoir area or around the periphery in an imagery taken during the draw-down cycle, the imagery for the next cloud-free date is examined. If the area covered by the cloud in a particular imagery has water at the same location on the next date's imagery, the pixels below the cloud are classified as water pixels. The reason is that the reservoir water surface area decreases with time during the draw-down cycle and so the pixels having water on a given date will also have water on the previous date.

Some pixels may be affected by noise in the data and are edited in a similar way using the imagery of previous or subsequent days. Due to the presence of local depressions and islands around the reservoir periphery, a few water pixels might be present near the reservoir area. Such pixels that do not form part of the continuous water spread should be removed. Many streams join the reservoir from different directions around the periphery. Beyond a certain point, these do not form a part of the reservoir. The imagery is edited to suitably remove such tails.

The number of water pixels in an imagery can be obtained from the image histogram. The water spread area is calculated by multiplying the number of pixels by the area of one pixel. The reservoir capacity between two consecutive contours (ΔV) can be computed using the trapezoidal formula (eq. 12.25). The contours can also be used to prepare the DEM of the area. The DEM of two different dates can be compared to determine the depth of sediment deposition at various points.

12.5.3 Case Study – Assessment of Sedimentation in Dharoi Reservoir

Multi-temporal data acquired by the LISS-II sensor (having a resolution of 36.25 m) of IRS-1A satellite were used by Goel and Jain (1996) to assess sedimentation in Dharoi reservoir. In India, more than 80 per cent of the annual rainfall is received during the four monsoon months of June to September. Therefore, the water level in a reservoir can be expected to be highest after the monsoon season after which it gradually depletes till onset of the next monsoon season. After carefully examining the availability of good quality data, the data of eight dates were chosen to capture the maximum variation in the water level: May 02, 1988; October 03, 1988; October 12, 1989; November 25, 1989; January 30, 1990; February 21, 1990; March 15, 1990; and April 28, 1990.

The presence of sediments in water changes the backscattering characteristics of water. Suspended particles tend to increase the total scatter and backscatter, reduce the average path length and consequently change the spectral distribution of light. Thus, turbid water is more reflective than clear water. The measured signal at any wavelength depends on particle size and concentration. Band 1 (0.45 μm - 0.52 μm) and band 2 (0.53 - 0.59μm) of the LISS-II sensor provide information about the suspended sediments in water. Band 3 (0.62μm - 0.68μm) and 4 (0.77μm - 0.86μm) do not show a clear pattern of suspended sediments due to limited penetration power.

At greater wavelengths, water apparently behaves as a black body absorber and the reflected solar energy is very low. In band 4 (0.77μm - 0.86μm) of IRS-1A, sunlight is almost completely absorbed by water and the boundary between water and other surface features is clear. Hence, band 4 was used to calculate the water surface area for satellite data of different dates. To differentiate water pixels from the adjacent wetland pixels, a comparative analysis of the digital numbers in different bands was carried out. The behaviour of the reflectance curves of water and soil/vegetation is different from band 2 onwards. Beyond band 2, as wavelength increases, water reflectance curves show a downward trend while soil/vegetation curves show an upward trend. This characteristic was used to differentiate water pixels in band 4 and density slicing was employed to obtain the water surface areas for the eight different dates. Only continuous extents of water pixels were considered to calculate the area. Water surface areas were obtained by multiplying the number of water pixels by the area of individual pixels.

The volume of the reservoir between two consecutive levels was calculated using the prismoidal formula (eq. 12.25). The volume of water below the lowest observed level (172.90 m) was assumed to be the same as at the time of construction of dam. By successive addition, the volume up to the highest observed level (187.98 m) was determined. Original and revised elevation-capacity curves for the Dharoi reservoir are given in Fig. 12.15. It was found that about 57.27 million m^3 of sediments were deposited in the reservoir over a span of 14 years. Assuming a uniform rate of sedimentation, the average sedimentation rate works out to 4.091 million m^3/year.

Recently, better algorithms than density slicing that use data of different spectral bands have been suggested. A *Normalised Difference Water Index (NDWI)* was proposed by Goel et al. (2002):

$$\text{NDWI} = (B2 - B3)/(B2 + B3) \tag{12.27}$$

where *B2* and *B3* represent reflectivity in bands 2 and 3, respectively. Normally, NDWI for

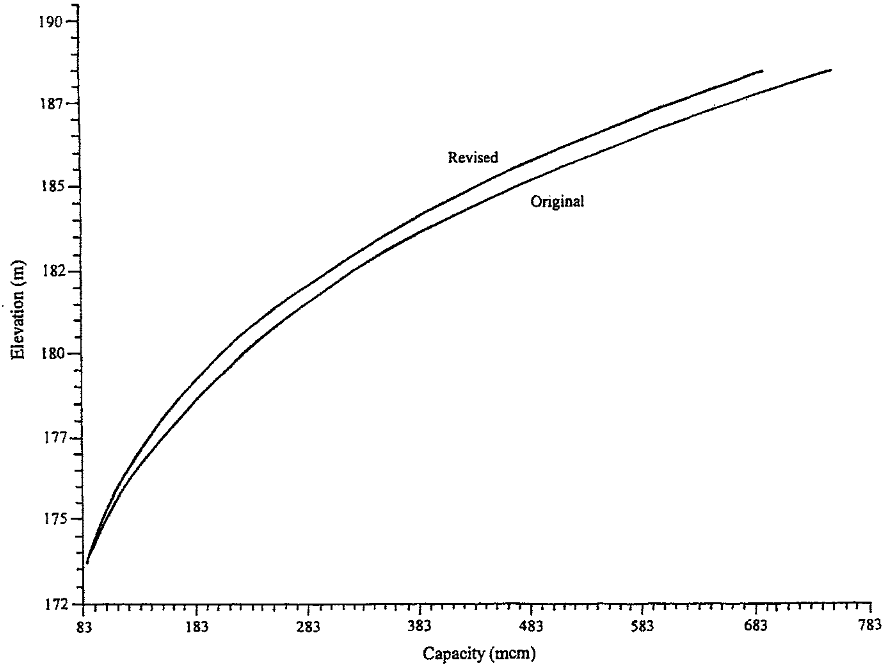

Fig. 12.15 Original and revised elevation-capacity curves for the Dharoi reservoir.

water pixels is either equal to or greater than a threshold value. In addition, a model can be applied to check the DN values of different bands to ascertain whether a pixel represents water or not. The biggest advantage of using a model is that it avoids the necessity of subjectively selecting different limits in different images as required in density slicing. The results of assessment of reservoir sedimentation using satellite data have also been given by Goel and Jain (1998), and Gupta (1999).

12.6 METHODS TO CONTROL SEDIMENT INFLOW INTO A RESERVOIR

The problem of reservoir sedimentation is complex but manageable. The problem can be controlled to a large extent by judicious design, construction, and management of reservoirs. The Yellow River in China is notorious for very high volumes of sediments in its water. The Sanmenxia Dam was the first dam built in the middle reach of this river. Immediately after the impounding commenced, about 1.8 billion metric tonnes of sediments accumulated during the first 18 months. This represented a trap efficiency of 93%. To achieve the balance between sediment inflow and outflow, the dam was extensively reconstructed by providing high capacity bottom outlets and reservoir operation was substantially changed. As a result, sediment balance was achieved in 1970 and Sanmenxia was the first major reservoir in the world where this was accomplished.

There are various ways to manage the sedimentation problem and the effectiveness of an approach depends on the site conditions. Thus, it is not possible to identify a technique which will work everywhere. Broadly, the methods to control the reservoir sedimentation are as follows:

- Control the sediment inflow into the reservoir,
- Do not allow the entering sediment to settle in the reservoir, and
- Remove the settled sediment from the reservoir.

Regarding the first approach, there are three ways to prevent the sediment from entering the reservoir: i) construct reservoirs away from streams, ii) place physical barriers in the way of sediment movement, and iii) manage watersheds to check soil erosion. A discussion on these follows.

12.6.1 Off-stream Reservoirs

If the site conditions permit, a reservoir can be constructed away from the main stream. Water of low sediment concentration is diverted from the main river to the reservoir as shown in Fig. 12.16. The flows containing high sediment load are excluded from diversion. There are many methods of sediment exclusion from the diverted water. These basically work on the premise that the distribution of sediment is not uniform across the cross-section in a channel and water is, therefore, withdrawn from the zones that contain a lower sediment concentration. An additional advantage of an off-stream reservoir is that only a desired amount of flow is diverted to it and, therefore, its capacity can be limited. Furthermore, this reservoir does not require a large spillway and hence the construction cost can be considerably small.

12.6.2 Check Dams

A check dam is a small dam of a few metres height which is constructed across a stream in the headwater region to reduce flow velocity and control channel erosion. Due to fall in velocity, most of the sediment is deposited behind the check dam and relatively clear water comes out downstream. These dams can be highly effective in controlling reservoir sedimentation. The cost of a small check dam is not very high. Some saving is possible by using locally available construction material. Therefore, before constructing a series of such dams, the watershed should be thoroughly investigated to identify the most suitable location for such structures. These dams are more efficient for sediment trapping if they are spaced farther apart. These are not a long-term solution to the problem because they do not control the sediment erosion and once the reservoir behind the check dam is filled with sediments, it no longer serves the purpose.

12.6.3 Watershed Management to Reduce Soil Erosion

This is one of the widely followed methods and is the only effective alternative in many instances. The term watershed management has wide implications and its objectives may be to reduce soil erosion, increase infiltration, and improve water yield and quality. The programs may include point treatment as well as treatment of non-point sources. The watershed management programs covering large areas are expensive and the benefits are available only after some time lag. These programs, besides being beneficial for reservoir

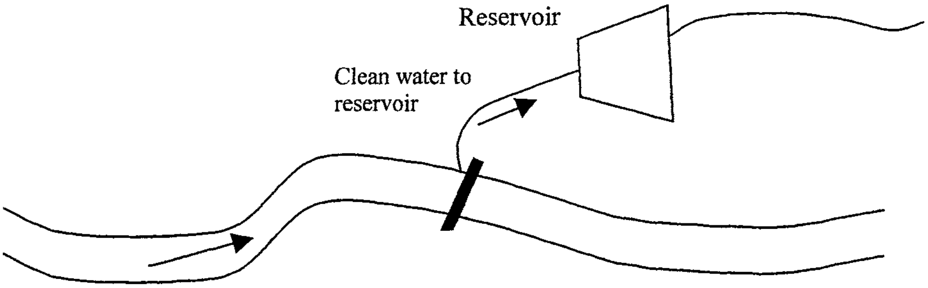

Fig. 12.16 An off-stream reservoir.

sedimentation, yield many other advantages. The techniques, such as contour bunding and afforestation were successfully applied in the catchment of Tungabhadra dam in India and siltation rate was reduced to 1/3 of the original value. Large scale soil conservation measures in the middle reaches of the Yellow River in China reduced the sediment loads of tributaries, such as Wuding, Fenhe, Wingshui, to 50% of their original value.

Soil conservation is an effective method to prevent movement of soil particles and transport of sediment to the reservoir. Before any major soil conservation program is launched, the underlying physical process should be understood. A good approach to reduce soil erosion is to plan erosion control techniques specifically designed for the soil, climate, and topography of the basin. Agricultural activities should be planned by providing suitable cover to erodible soils. The protection of land through forest and agriculture is a cheap alternative in the long term. A good strategy is to increase the vegetation cover to the extent possible, increase infiltration, and reduce the highly erosive concentrated flows. Terracing, limiting slope length, and steepness can control concentrated flows.

Unless a watershed management program is properly planned and executed, the benefits may be small despite large investments. Some areas, e.g., Himalayas, are highly erosive due to geological and climate factors and it may, therefore, not be always possible to appreciably reduce soil erosion. In any case, one may not expect complete stoppage of soil erosion in any region.

12.6.4 Vegetative Measures

These techniques basically make use of vegetation or mulch to protect soil by diminishing the erosive forces. Extensive and sustained efforts over a long period of time are required to control soil loss if sizeable land area is degraded. Vegetation is more effective in controlling distributed flows; this measure in isolation may not be able to have any worthwhile control on erosion due to concentrated flow. For best results, the choice of vegetation should be a function of climate, soil, and topography.

Forests for Erosion Control: The erosion of soil in a forested area is less as the tree canopy intercepts rainfall and the drops fall down slowly. To achieve a significant reduction in erosion, the forests planted for soil and water conservation should cover large area, have multiple levels, a dense canopy, and a high density. The trees selected should be able to grow under prevailing climatic conditions, thin top soil, strong winds, and should be fast growing. Their root system should be highly developed to consolidate the soil. Their fallen leaves can be used as forage, fertiliser, and fuel. The trees which give other useful products, such as oil, are preferred in most cases.

Highly resistant shrubs are usually planted in arid areas while arbors are common in humid areas. Depending on climate, a mixture of arbors, shrubs, coniferous trees, and broadleaf trees may be planted to increase the ground coverage. The management of forests and croplands requires significant efforts in the beginning but is cheap in the long-term besides additional benefits. These measures improve the environment quality, availability of food and fodder as well as increase in the farmers' income. Most forests are self-renewing and require little maintenance after initial years.

Farming Practices: Land is cultivated without due attention to soil and water conservation in many hilly catchments. Due to the high population density in some regions, even those lands are being cultivated which are not suitable for agriculture. The practice of agriculture along the contours is known as contouring. This is an old concept. The design of terraces depends on climate, soil, crops, and farming system. It is very effective in reducing surface runoff and formation of rills and gullies. Strip cropping involves planting alternate strips of different crops which may follow the contour pattern. In this arrangement, some part of the field is always covered with a crop.

The common methods for land preparation are level terraces, level ditches, and fish-scale pits. Level terraces are built along contours by balanced cutting and filling. The exterior edge of the terrace should be higher than the interior edge by 9-18 cm to conserve moisture. Usually, the width of terrace is 0.6 - 1.2 m and the height 1.2 - 1.8 m.

Highly Resistant Grasses: Grasses are an important component in vegetative measures for soil and water conservation due to fast growth. These are also planted for supply of forage and fuel. Grass seeds should be highly resistant to adverse natural conditions. Land preparation is necessary before seeding of grass, and some manure and fertilizer are applied. The required thickness of covering to suit local conditions should be ascertained.

Sediment Trapping by Vegetative Screens: Vegetative screens considerably reduce the flow velocity and cause the sediment to deposit behind them. If such screens of a few km width are put before the reservoir periphery, they prevent the sediment from entering the reservoir. The effectiveness of the screen depends upon its spatial extent.

12.6.5 Engineering Measures

These include slope surface engineering works, gully engineering works, and works for controlling slope disintegration.

Slope Surface Engineering Works: Terracing is an important measure to raise grain yield, to prevent soil erosion, to preserve soil fertility, and to maintain long-term stable production. There are three kinds of terraces (a) bench terraced farmlands; (b) sloping terraced farmland; (c) combination level terraced farmlands and natural slope land.

Bench terrace is the basic type of farmland in mountains. A bench terrace with its level platform and projected or ridged rim may hold rainwater for irrigation. Proper drainage should be provided in rainy areas. Under sloping or retention terraced farmlands, only riser dikes are built and no land levelling is made. The land surface will be flattened gradually by deep ploughing over the years. The spacing between riser dikes varies with the natural slope. In parallel with the siltation of sloping terraces, the riser dikes are made higher. The sloping terrace is less effective than the bench terrace in both soil and water conservation. It is mostly adopted in regions where the per capita land availability is high.

Gully Engineering Works: The check dams are the most effective gully engineering works. Their purpose is to retain silt, to fix gully bed, to raise erosion datum, to stop downward cutting of gully bed, or to prevent slope disintegration. In addition, storage of excess runoff in suitably located farm ponds also helps in soil conservation.

12.6.6 Watershed Prioritization

Since watershed treatment requires huge resources, it is desirable to target these programs in the areas that produce large quantities of sediments. Alternately, the treatment programs can be taken up in phases; zones that produce more sediments are attended first and so on. An assessment of soil loss from sub-watersheds is made and a priority ranking is prepared.

In view of extensive data requirements of sediment yield models, an alternate is to use topographical/ morphometric, soil, and vegetation data for qualitative estimation of erosion. Manavalan et al. (1993) presented an empirical model named *WA*tershed *R*esponse *A*nalysis (WARA) model (see Fig. 12.17) that uses data of slope angle, drainage density, soil, and vegetation to study erosion susceptibility and surface runoff potential of a watershed. This model lacks a rigorous theoretical basis. A key feature of this study was that satellite imageries were used to prepare thematic input maps. Thematic maps were analyzed to assign weights to sub-catchments and these formed the basis for prioritization. Typical input theme layers are: watershed boundary, drainage, slope, vegetation, and soil texture. The preparation of thematic layers is discussed below. The number of categories into which the layers are divided depends on the variation of the relevant property.

Vegetation Map: The presence of vegetation reduces the sediment detachment and transportation. In a multi-spectral satellite image, a Normalized Difference Vegetation Index (NDVI) is an indicator of vegetation condition. The NDVI is computed as:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}) \qquad (12.28)$$

where NIR and RED are reflectances in near infrared (say 0.77-0.86 μm range) and red (0.62-0.68 μm) bands in an imagery. The normalization minimizes the effect of the

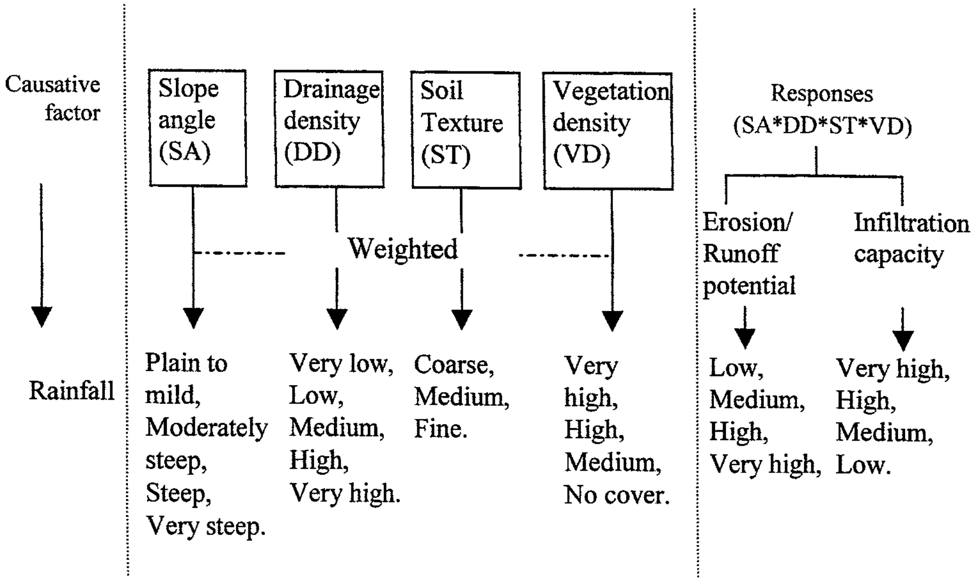

Fig. 12.17 Watershed response analysis model [adapted from Manavalan et al. 1993].

illumination geometry as well as surface topography although it does not eliminate the additive effects due to atmospheric attenuation. The NDVI image can be density sliced in vegetation classes and relative weights are given to each vegetation category to calculate the area-weighted value of the vegetation. The *Area Weighted Vegetation* (AWV) for a watershed having five classes is calculated as:

$$AWV = (A_1*V_1 + \dots + A_5*V_5) / (A_1 + \dots + A_5) \qquad (12.29)$$

where $A_1, \dots, A_5$ are the areas under each vegetation category, and $V_1, \dots, V_5$ are the weights for each vegetation category. An example of relative weights is given in Table 12.9 which is based on the reasoning that the watershed with a denser vegetation will have lesser erosion and must be given low priority in soil conservation measures and vice versa.

Table 12.9 Weights for Vegetation Categories.

Vegetation Density	Weight
Very high	5
High	4
Medium	3
Small	2
Very less or no vegetation	1

Soil Brightness Index Maps: Physical properties of the soil affect the extent to which it can be detached, dispersed, and transported. The Soil Brightness Index (SBI) indicates the susceptibility of soil to erosion. Tone and texture are the major soil properties which affect its brightness. To compute SBI, it is necessary to transform the data into different axes. For Landsat MSS data, *Tasseled Cap transformation* is widely used because it captures the greatest amount of data variability in fewest features and enhances data interpretability. The maximum variation can be captured in brightness and greenness, the two major axes of the transformed data set. The transformation used by Sharma et al. (1990) to calculate SBI using Indian Remote Sensing Satellite (IRS) - 1B, LISS - II data is:

$$\text{SBI} = 0.2623*\text{B1} + 0.6432*\text{B2} + 0.6302*\text{B3} + 0.3471*\text{B4} \tag{12.30}$$

where $B1$, $B2$, $B3$, and $B4$ are bands 1, 2, 3, and 4 of the sensor, respectively. Similar to NDVI, the SBI image for a watershed is classified into different classes and relative weights are given to each SBI category. Similar to vegetation, the Area Weighted Soil (AWS_o) values are calculated for all watersheds. High AWS_o is given higher weight and vice versa.

Slope Map: Slope is an important factor governing soil erosion in a watershed. Steeper the slope, more will be the erosion. The slope map of a watershed can be prepared from a contour map. Since a watershed contains many slope categories, the area-weighted slope (AWS) can be calculated using the following equation for a 5-category case:

$$\text{AWS} = (\text{A}_1 *\text{wS}_1 + \ldots + \text{A}_5*\text{wS}_5) / (\text{A}_1 + \ldots + \text{A}_5) \tag{12.31}$$

where AWS is the area weighted slope, $A_1, \ldots, A_5$ are the areas under slope categories, $wS_1, \ldots, wS_5$ are the weights for slope categories. The slope image is classified into different categories and weights are assigned.

Morphological/Topographical Parameters: Morphological and topographical parameters can be obtained from topographic maps at an appropriate scale. For stream ordering, the Strahler system, which is a modified form of Horton's method, can be used. Using the GIS database, morphological characteristics of watersheds like the drainage density, form factor, circulatory ratio, and elongation ratio can be estimated and a DEM can be generated.

The drainage pattern is an indicator of flow characteristics. More the overland flow, more will be the silt load travelling to the channel. Drainage density (D_d) is the ratio of total length of streams to the total drainage area and is expressed in length per unit area:

$$D_d = \text{Total stream length of all order-streams / Watershed area} \tag{12.32}$$

A higher drainage density implies a higher number of streams per unit area and thus a rapid storm response which is conducive for higher erosion. The drainage map can be prepared from topographic maps. The shape of a watershed also governs the movement of silt -- more elongated a watershed is, less is the possibility of silt reaching the outlet. A circular watershed has less time of concentration and more possibility of silt load reaching the outlet point. The form factor describes the shape of a watershed and indicates its erosion potential; higher form factor induces sediment delivery of lesser erosion and vice versa. The form factor is calculated as:

$$\text{Form Factor} = \text{Area} / \text{L}^2 \tag{12.33}$$

where L is the length of basin. The form factor values can also be classified in five classes and weights assigned for different ranges of form factors.

Prioritisation: The process of prioritisation is integration of all the themes and weights. Based on the evaluation of different parameters as described above, priority values can be assigned to the sub-watersheds. Higher the sum weight, more prone is the sub-watershed to soil erosion and higher should be the priority for its treatment.

12.7 SEDIMENT ROUTING

Sediment routing is an effective method to control reservoir sedimentation. It includes the methods to manage the hydraulic behavior of the reservoir and its geometry so as to allow the maximum sediments to pass through the storage. The sediment load transported by stream varies with time; it is the highest during the period of intense precipitation and is very small during low flows. Therefore, to ensure that the least amount of sediment gets deposited in the reservoir, it is important to manage sediment-laden flow differently from the flow containing small amounts of sediments. The concepts of sediment routing were developed in China and the guiding principle is: *discharge the muddy water, impound the clear water*. An advantage of sediment routing is that the characteristics of the sediment being transported are not significantly changed. In this sense, it is the most environmental friendly approach.

The sediment routing techniques can be classified into two groups: sediment pass–through and sediment by-pass. Sediment is passed through the reservoir by either drawing down the reservoir water level or venting the turbid density currents.

12.7.1 Reservoir Drawdown

In the reservoir drawdown approach, the water level is bought down so as to pass the turbid flow through the reservoir without deposition. Typically, the reservoir level is brought down in the beginning of a flood event because the rising limb of the hydrograph carries larger amounts of sediments than does the falling limb. Since a significant amount of water may be lost during drawdown, it is important that the reservoir is filled up in the falling stage of the hydrograph and the purposes that it is required to serve do not suffer. In some cases, reservoir drawdown for sediment management is incorporated in the rule curve and it becomes an integral part of reservoir operation.

12.7.2 Density Currents

A density current is defined as the gravity flow of fluid under, over, or through another fluid of approximately equal density or the density of which differs by a small amount from that of the other fluid. Further, it is essential that two fluids are miscible and that the density difference be due to differences in temperature, and/or sediment concentration of the two fluids, but independent of pressure, density, and elastic properties of the fluid. Density currents are generated when sediment-laden water enters a relatively still water body. A sediment-laden inflow with density greater than the reservoir water descends to the lower water layers and moves towards the dam. The density current venting approach (Fig. 12.18) provides a clear un-hindered path to sediment-laden flows which are released through the low level outlets of the dam giving least opportunity to the current to dump sediments.

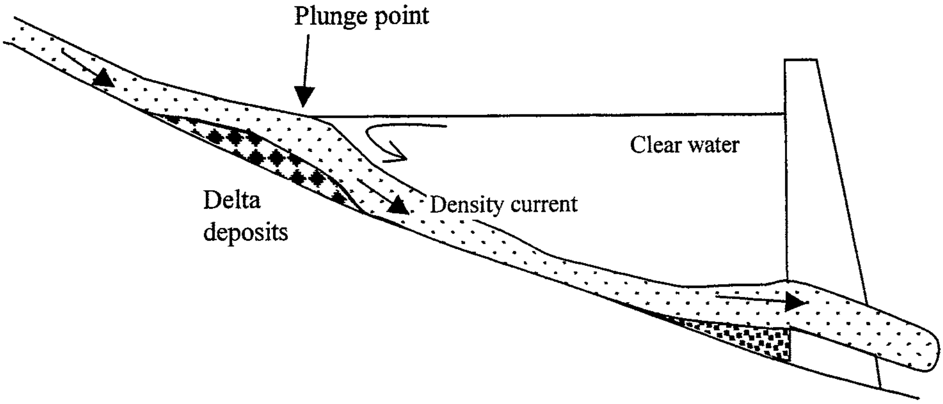

Fig. 12.18 Venting of density current through bottom outlet in a reservoir.

Density currents that transport sediments from upstream parts of the reservoir to downstream parts closer to the dam are important for sedimentation management. Upon entering the reservoir, the inflowing muddy water may plunge into the clear still water of the lake and travel below the surface due to higher density. Partial mixing may occur due to turbulence. As this current loses velocity, the ability to carry sediments reduces and coarser particles are deposited. Depending on the residual sediment concentration, the current may dissipate or continue to move forward. After reaching the dam, the current (including the sediments) can be let out through low-level outlets. The outlets should be located at the right elevation and operated to provide an unhindered path to the density current before it has an opportunity to settle down in the reservoir. This approach has been followed in many reservoirs, e.g., Elephant Butte and Lake Mead reservoirs in the United States, and Guanting, Yongding, and Sanmenxia reservoirs in China.

The plunge point or the place where sediment laden flow plunges underneath the clear water reservoir is at a section where (Garde, 1995):

$$U_o / [(\Delta\gamma_o / \gamma) g h_o] = 0.60 \tag{12.34}$$

where U_o and h_o are the velocity and depth of flow at the plunge section; γ is the unit weight of sediment laden flow; and $\Delta\gamma_0$ is the difference in unit weights of sediment laden flow and water in reservoir. The velocity of density current (U') is given by

$$U' = [(8\Delta\gamma / f\gamma)^* g q S_0]^{1/3} \tag{12.35}$$

where f is Darcy-Weisbach resistance coefficient including the resistance at the bottom and the interface; q is the discharge of density current per unit width; and S_o is the stream slope.

The venting efficiency is the ratio of inflowing and outflowing turbidity currents. It depends on the length of the reservoir: in reservoirs of up to about 1 km length, close to 100% efficiency has been obtained. The efficiency decreases substantially beyond the reservoir length of 10 km. This efficiency also decreases as the average outflow to inflow ratio decreases. Morris and Fan (1998) cite the cases where it has been possible to release more than half of the total sediment load in an individual turbid current by proper operation. This approach is considered to be environment-friendly, since the sediment related properties of outflows are close to those of inflows.

12.7.3 Sediment By-pass

This is an intuitively appealing arrangement which basically prohibits sediment laden flow from entering the reservoir. It consists of a diversion structure upstream of the dam (Fig. 12.19) by means of which the flows with heavy sediment concentration are diverted to a by-pass channel or conduit which joins the main river downstream of the dam. As a result, the flows entering the reservoir are relatively clean and naturally, the sedimentation problem will not be serious. This scheme has been used for the Tezden reservoir in the (former) USSR and the Amsteg reservoir in Switzerland.

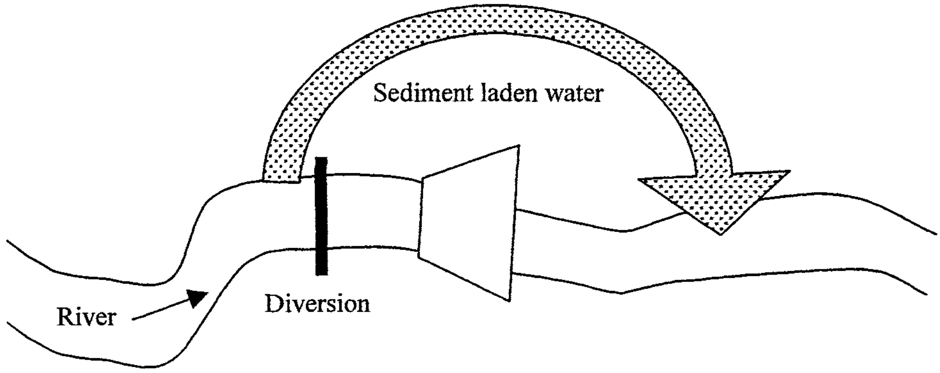

Fig. 12.19 Sediment by-pass.

12.8 RECOVERY OF STORAGE CAPACITY

Two methods of recovering the storage capacity of a reservoir are briefly described in what follows.

12.8.1 Flushing

The aim of flushing is to establish for a short time the same flow conditions in the reservoir area (at least the channel portion) as had existed before the impoundment began. Emptying and flushing operations may be used in reservoirs where a balance between deposition and erosion cannot be obtained. This enables the river current to erode some of the deposited sediment and flush it out of the reservoir through low-level outlets. The channel area thus scoured is the re-gain of the storage capacity. The efficiency of sediment flushing depends on the topography of the reservoir, the capacity and elevation of outlets, and the characteristics of the inflowing sediments. For the best results, the flushing sluices should be located as deep in the dam as possible and should be sufficiently wide so that the minimum backwater is produced. Furthermore, two sluices side-by-side are preferred to sluices at different levels. The deposition on the flood plains is not affected by the flushing operation. The flushing operation lasts from a few hours to several days. Note that the lowering of the reservoir level adversely affects conservation purposes such as power generation and irrigation. Therefore, this approach is particularly suitable for reservoirs whose CI ratio is small (usually less than 0.3) since these are quickly refilled after flushing is over. According to Garde (1995), not more than 10-15% of sediment can be removed in this manner under the most favourable conditions.

Normally the flushing is carried out once every year. It has three stages. During the draw-down stage, the reservoir level is lowered by releasing water through the under sluices or hydropower plants for some time. In the final drawdown phase, the water level is rapidly lowered using the bottom outlets and it lasts over a few hours. In the erosion stage, the riverine flow is established along the length of the reservoir and the flow erodes the sediment in the channel cross-section due to high velocity. The width of erosion depends upon magnitude of flows. If the flows are large, a wider cross-section of the channel is eroded, otherwise the erosion may be confined to a narrow region. This stage may last over several days. In the third and final stage when the storage recovery is satisfactory, the bottom outlets are closed to refill the reservoir. Flushing is most effective when the low level outlets are placed near the original bed of the river and reservoir is completely emptied. In many reservoirs, flushing is the only viable means of controlling sedimentation. For instance, a number of sediment management strategies including watershed management, construction of check dams and dredging were considered for the Tarbela Dam in Pakistan. However, none of these was found to be effective because the dam is located on the Indus River in a tectonically active region of Himalayas. Due to very large volume of sediment being transported, dredging was an expensive proposition.

Flushing efficiency (F_e) is defined as the ratio of deposited volume that is eroded to the water volume used during flushing over the specified time intervals. Let inflow and outflow water volumes be V_i and V_O (m^3), inflow and outflow total sediment concentration be C_i and C_O (kg/m^3), and the bulk density of the deposited material ρ (kg/m^3). Then, the flushing efficiency is:

$$F_e = (V_0 C_o - V_i\, C_i\,)/\,(V_0\, \rho) \tag{12.36}$$

Typical values of flushing efficiency vary in the range 0.006 to 0.12. Morris and Fan (1998) describe the details of flushing operation at the Cachi, Gebidam, and Sanmenxia reservoirs. As a result of flushing, the trap efficiency of Cachi hydropower reservoir constructed on Reventzon River in Costa Rica was reduced from 82% to 27%. This approach is also in use in the reservoirs of Damodar valley system in India.

Flushing is not considered environmentally friendly because a large amount of accumulated sediment is released during a short period when the natural flow may be smaller and this may cause problems in the downstream areas. Further, the characteristics of the sediment released from the reservoir are significantly different from those of the incoming flows. The release of large amounts of sediments in a shorter time can choke irrigation canals and is harmful to the biological life in the downstream channel.

12.8.2 Dredging

Dredging is the process of removing the sediment from a water body (reservoir or channel), transporting, and depositing it at another location far away. Generally, dredging is an expensive means of recovering the storage capacity unless the deposits removed can be used for beneficial purposes. However, with the increase in water demand and reduction in construction of new projects, it is expected that the number of incidents where dredging is taken up will increase. Dredging may be resorted to when other methods of sediment management are not viable or successful.

Dredging is usually focussed on small areas in the reservoir, e.g., the intake structure, the regions that are being used for recreational purposes, due to cost considerations. Of course, there are problems in locating suitable sites to place the excavated material. Ideally such sites should be near the reservoir to reduce the cost of transportation. The sediment that is removed may be put in the river downstream of the dam or may be dumped in a depression away from the river. If the material is dumped in the downstream river channel, it is carried away by the river flow. Some coarse sediments may be used as construction material.

While planning a dredging program, the location and depth from which the sediment is to be removed, the volume to be cleared, and grain size distribution of the sediment should be ascertained by sampling. The equipment to be used, rating of pumps, and other considerations critically depend on it. The dredging equipment to be employed depends on the depth of excavation, the distance of dumpsite and the elevation difference between the excavation area and dump site. The means of transporting the sediment depends on the dredging technique. Trucks may be used in dry excavation while pipelines are employed to move slurry in wet dredging. The dredging operations should be timed when the fluctuations in the reservoir water level are small and gradual.

Dredging can be carried out without affecting the normal operation of the reservoir. If the area to be cleared is normally dry, the earth moving equipment can be deployed. Sometimes, the reservoir is specifically emptied for this purpose. However, unless the area is totally dry for some time, such excavation is problematic, because the heavy earth moving vehicles may get bogged down in swamps or may skid on clayey soils. The cost of dry excavation depends on the volume and type of material to be handled, the distance to the dump site, and the elevation differences between the excavation and the dump sites.

Hydraulic and mechanical dredges are employed for wet dredging. In hydraulic dredging, the sediment is excavated, mixed with water to form slurry which is transported to the dump site. Mechanical dredges use small buckets mounted on a chain to dig, lift, and transport the excavated material.

From the point of view of convenience, the discharge of dredged material downstream to the dam is the easiest option. However, this option just transfers the problems of sediments from one place to another. The sediment that is moved by the river may again cause problem in the downstream areas, may be deposited in canals or damage water supply networks. Therefore, before depositing the sediment downstream to the dam, its consequences should be properly assessed. Sometimes the dredged sediment is dumped in a dry valley. As far as possible, such sediment should not be deposited in wetlands and should be ensured that the future use of the dumped area does not get hampered. As the availability of dump sites is limited in most cases, dredging is not a preferred or permanent solution to the problem.

12.9 CLOSURE

Sedimentation of reservoirs is a cause of concern in many regions of the world. In these areas, natural processes are predominantly adverse. However, dams are required to be constructed to meet various demands as well as control flooding. It is necessary that remedial design and management measures are taken so that the life of artificial reservoirs is prolonged and they do not silt up rapidly.

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