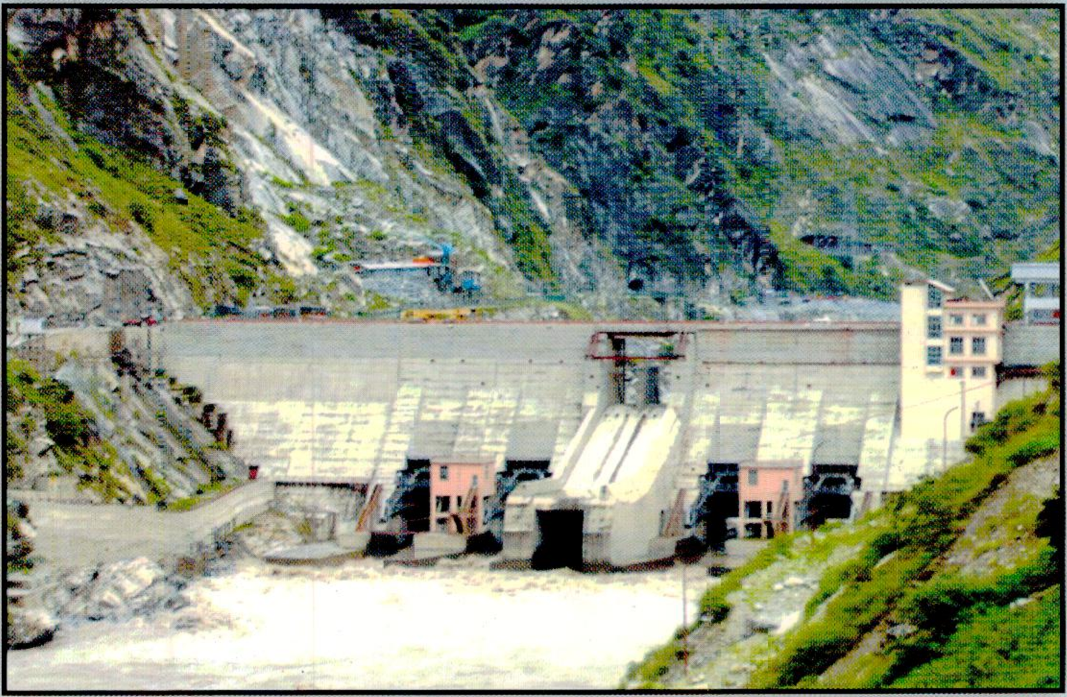
Scientific contribution
No: INCOH/SAR-30/2010

STATE OF ART REPORT

ON
RESERVOIR SEDIMENTATION



BY
K. G. RANGA RAJU, U. C. KOTHYARI AND M. K. MITTAL

Publication of
Indian National Committee on Hydrology (INCOH)
(IHP National Committee of India for UNESCO)
National Institute of Hydrology, Roorkee - 247 667
INDIA

INDIAN NATIONAL COMMITTEE ON HYDROLOGY (INCOH)

(IHP National Committee of India for UNESCO)

Constituted by the Ministry of Water Resources in 1982

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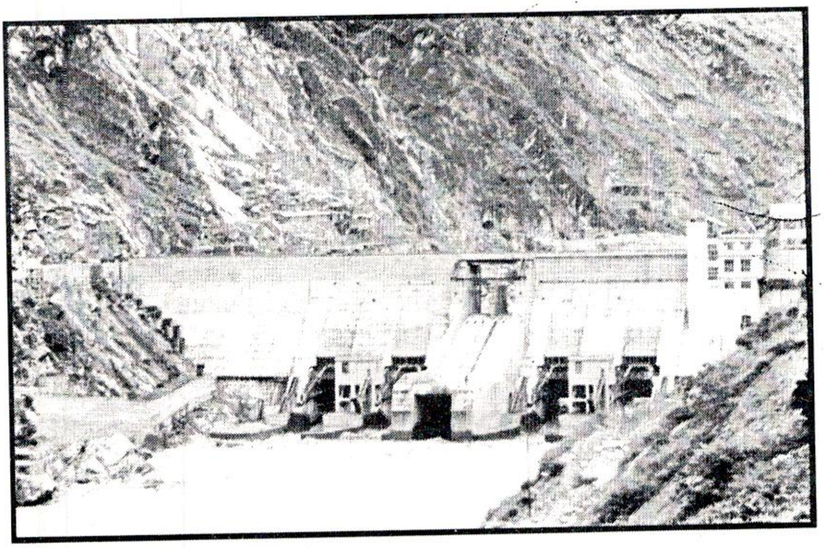

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INDIAN NATIONAL COMMITTEE ON HYDROLOGY (INCOH)
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PREFACE

The Indian National Committee on Hydrology (INCOH) is the apex body under the Ministry of Water Resources (MoWR), Government of India with the responsibility of coordinating activities concerning hydrology and water resources development in the country. The committee has its members drawn from central and state government agencies as well as experts from academic and research organizations. INCOH provides technical support to MoWR in identifying the R&D schemes and studies for funding. It publishes the Journal of Hydrological Research & Development as well as State of Art Reports on some of the important topics of hydrology. The committee is also participating in the activities of International Hydrological Programme (IHP) of UNESCO by 'organizing regional courses and workshops and conducting R&D works on themes of IHP. In pursuance of its objectives of updating the state-of-art in hydrology of the world in general and India in particular, INCOH encourages the experts to prepare the reports. As a step in this direction, the State of Art report entitled, **"Reservoir Sedimentation"** has been prepared by Prof. K.G. Ranga Raju, Prof. U.C. Kothyari and Prof. M.K. Mittal.

Dams and reservoir are built for storing water for use in irrigation, hydropower generation, water supply etc. However, the existing reservoirs world wide are loosing their storage capacity due to sedimentation. According to resent estimates China and India are annually loosing 0.5% to 2.3% of available reservoir storage capacity. Development of new reservoirs was the focus during the past century; the present century however, needs to focus on the sediment management for sustainable use of the existing reservoirs. It is very essential to be able to predict the manner in which reservoirs get silted with changing hydrologic and climate conditions in the catchment area. The presently available methods are not completely adequate to make such predictions. Because of the complexity of the process, the results from any method or methods developed for prediction of sedimentation rate and pattern strongly depends on input data used, climatic, topographic and lithologic conditions of the watershed etc.

The present status report reviews the literature available on various aspects of reservoir sedimentation such as sediment yield, patterns of sediment deposition profile and their prediction, and methods of controlling and reducing the reservoir sedimentation. Emphasis is given on beginning the integrated programs for mitigation of this problem. It is expected that this state-of-art report would serve as a useful reference material to practicing engineers, researchers, field engineers, planners, stakeholders and implementing authorities, who are involved in management of reservoir sedimentation.

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CONTENTS

ABSTRACT

Rivers have sustained human civilizations for several centuries. The needs of drinking water, irrigation, electric power and navigation are mostly met by river systems. Reservoirs have to be built on rivers to cater to the mentioned demands. Hydropower developments by run-of-the-river projects also involve the construction of a reservoir of small or medium size and, in case the power house is located far away from the reservoir, the water will have to be conducted through a tunnel or a canal in these projects. Alluvial rivers as well as rivers in gravel and boulder stage pose several challenging problems in the design of reservoirs built on them on account of the complex role played by the sediment load carried by them. Construction of a dam and withdrawal of water from the reservoir invariably disturbs the equilibrium of the river leading to aggradation and degradation in different reaches of the river. As such, design of reservoirs in the case of alluvial, gravel as well as boulder bed rivers requires a clear understanding of the influence of sediment load carried by them and incorporating the sediment load as one of the parameters in reservoir design. Several aspects of practical importance in such designs are addressed in this report. In addition, the topics on mathematical modeling and sediment management in reservoirs are dealt in detail. The contents of the report, however, are influenced to a significant extent by the Indian practice in handling these problems.

1.0 INTRODUCTION

A reservoir is formed by the construction of a dam across a river. The water surface slope upstream of the dam is reduced due to the formation of the reservoir resulting in the creation of a backwater surface profile. The flow depths in the reservoir reach (backwater reach) are larger than those in the undisturbed portion of the river further upstream. As a result reduction in flow velocity occurs in the reservoir reach and the sediment transport capacity at any section in the flow there is smaller than at the any of the sections upstream. Thus the sediment transport capacity of the stream reduces after the formation of the reservoir resulting in deposition of the sediment within the reservoir and this process is termed as Reservoir Sedimentation (Garde and Ranga Raju, 2006).

Sediment deposition in reservoirs can have many harmful effects both upstream and downstream of the dam, if not addressed carefully both during the planning stage of the project and the operation stage. The effects of reservoir sedimentation are detrimental from hydrological, hydraulic, environmental as well as socio-economic considerations. This subject therefore needs to be understood comprehensively particularly in the context of Indian conditions, because the water resources planning and management are significantly affected by sedimentation in reservoirs.

This report covers the state of the technology available for estimation, control and management of sedimentation in reservoirs. The review focuses mainly on the sedimentation in storage reservoirs. The topic of sediment management in the run-of-the-river schemes for hydro power generation is also covered. However, the sediment management issues related to barrages and weirs are not discussed herein.

1.1 Functions of Reservoirs

The benefits attributable to dams and reservoirs are considerable. Stored water in reservoirs has improved the quality of life worldwide. The benefits from reservoirs for storage of water can be classified under three main headings described below in the context of the worldwide perspective (White, 2001).

1.1.1 ***Irrigation :*** About 20% of cultivated land worldwide is irrigated. This irrigated land produces about 33% of the worldwide food supply. Irrigation accounts for about 75% of the world water consumption, far outweighing the domestic and industrial consumption of water.

1.1.2 ***Hydropower :*** About 20% of the worldwide generation of electricity is attributable to hydroelectric schemes. This equates to about 7% of worldwide energy usage. In many hydroelectric projects, specially those originating in the Himalayan region of India, Bhutan, Pakistan etc., significant water storage is not created; instead the available energy head is directly utilized for power generation by diverting the river water into penstocks through a barrier across the river and intake on it. Such facilities are termed as the 'run-of-the-river projects' and numerous difficulties are elt in running of these projects in the Himalayan region due to sediment problems specially during the monsoon season. Hydropower generation is also an important objective of several of the storage reservoirs like Tehri, Govind Sagar (Bhakra) etc.

1.1.3 ***Flood control and storage:*** Many dams have been built with flood control and storage as the main motivator, e.g. the Hoover dam, the Tennessee Valley dams and some of the more recent dams in China. In India too, many big dams such as Hirakud, Tehri, Bhakra etc. also serve the purpose of flood control.

The useful life span of reservoirs is determined by the rate of sedimentation in the reservoir; the storage capacity reduces gradually and the reservoir efficiency decreases. Given the scarcity of good dam sites and the resistance to construction of new dams due to apprehensions of environmental degradation, it is no wonder that currently there is great interest in reservoir sedimentation. The ultimate objective is to increase the useful life of existing reservoirs as much as possible and plan the new ones for as long a life as possible.

1.2 Status of Reservoir Sedimentation

There are around 40,000 large reservoirs worldwide used for water supply, power generation, flood control, etc. Between a half and one percent of the total storage volume of existing projects is lost annually as a result of sedimentation and 300 to 400 new dams need to be constructed annually just to maintain current total storage (White, 2001). The increasing populations and increasing consumption per capita mean that the demand for storage is burgeoning despite the increasing use of alternative sources and the more efficient use of water. As per Morris (2005), by mid-21st century, over 30% of the world's reservoir capacity will have been lost to sedimentation.

A survey of the reservoirs in India has shown (Table 1.1 and Table 1.2) that the observed sedimentation rates are much higher than those assumed at the project design stage. Due to siltation useful live storage capacity in many reservoirs in India is reduced appreciably as shown in Table 1.1.

Table 1.1 Loss of capacity of some reservoirs in India (Singh et al., 1990)

Name of river	Name of reservoir	Year of impounding	Year of observation	Sedimentation yield rates ham/100 sq. km/year	
				Design	Observed
Beas	Beas	1974	1981	4.29	23.59
Chambal	Chambal	1960	1976	3.61	5.29
Barakar	Maithon	1956	1979	1.62	12.15
Damodar	Panchet	1956	1974	2.47	9.92
Manjira	Nizamsagar	1931	1973	0.29	6.34
Tungabhadra	Tungabhadra	1953	1972	4.29	6.11
Ramganga	Ramganga	1974	1974	4.79	17.30

Table 1.2 Rates of siltation of selected reservoirs in India (Singh et al., 1990)

River	Reservoir	Year of impounding	Year of survey	Loss of storage in per cent	
				Dead	Live
Sultej	Bhakra	1959	1978	17.82	3.69
Damodar	Panchet	1956	1966	27.00	13.00
Barakar	Maithon	1956	1979	32.00	14.00
Manjira	Nizamsagar	1931	1967	97.11	44.87
Tungabhadra	Tungabhadra	1953	1978	100.00	10.35

About 126 dams which are 30m or more in height were completed in India for irrigation, hydropower generation, flood control etc., before the year 1971. Many of these reservoirs now contain significant accumulations of sediment eroded from their catchments. Analysis of the sedimentation data (Shangle, 1991, Murthy, 1977) indicate highly varying sedimentation rates in these reservoirs. In some reservoirs, such as the 2.4×10^3 Mm^3 Ramganga reservoir in U.P., the data indicated a very small rate of sedimentation, while the 3.1×10^3 Mm^3 Srirama Sagar reservoir in Andhra Pradesh was found to have lost 25 % of its capacity during the first 14 years of its impounding. Based on a screening analysis of the available data, Morris (1995) concluded that a few reservoirs in India have lost as much as 50% of their capacity till 1995. By 2020 it is expected that 27 of the 116 reservoirs would have lost half their original capacity and by the year 2500, only about 20% of India's existing reservoirs would not have lost 50% of their capacity (Table 1.3).

1.3 Significant Factors Controlling Loss of Reservoir Storage

The reservoir sedimentation rate is dependent on the sediment yield from the catchment which, in turn, is dependent upon the rate of soil erosion and the transport by flow of the sediment eroded within the catchment. In regions where the catchments have remained stable, e.g. in Northern Europe and North America, the rate of loss of reservoir storage is sensibly constant. In other regions where deforestation has occurred, the rate of catchment soil erosion and consequently the rate of loss of reservoir storage has increased with time. The highest rates of loss of storage in percentage terms are found in the smallest reservoirs and the lowest rates in the largest. As per Alam (2004), of the 1105 reservoirs documented in India, 730 have a storage volume of less than 1233 Mm^3 and the average rate of loss of storage in them is in excess of 1% per annum. At the other extreme, 23 of the reservoirs have a storage volume in excess of 1233 Mm^3 and the average rate of loss of storage in them is 0.16% per annum (Alam, 2004). The worldwide average for the loss of storage due to sedimentation is between 0.5% and 1.0% per annum which is a considerable amount.

Table 1.3 Estimated rates of sedimentation in Indian reservoirs (Morris, 1995)

Reservoir	Year of construction	Catchment area (km^2)	Gross storage capacity (Mm^3)	Sedimentation rate (mm $year^{-1}$)	50% capacity lost (year)	Life of reservoir (years)
Srirama Sagar	1970	91,750	3,172	0.62	1998	56
Nizamsagar	1930	21,694	841	0.64	1960	61
Matatila	1956	20,720	1,133	0.44	2018	124
Hirakud	1956	83,395	8,105	0.66	2030	147
Girna	1965	4,729	609	0.80	2045	161
Tungabhadra	1953	28,179	3,760	1.01	2019	132
Panchet Hill	1956	10,966	1,497	1.05	2021	130
Bhakra	1958	56,980	9,800	0.60	2101	287
Maithon	1955	6,294	1,369	1.43	2031	152
Lower Bhavani	1953	4,200	931	0.44	2205	504
Mayurakshi	1954	1,860	608	1.63	2054	201
Gandhisagar	1960	23,025	7,740	0.96	2135	350
Koyna	1961	776	2,988	1.52	3228	2533

Whereas the last century was concerned with reservoir development, the 21st century will need to focus on sediment management with the objective of converting today's inventory of non-sustainable infrastructures for usages by future generations. The scientific community at large would require to work to create solutions for conserving existing water storage facilities in order to enable their functions to be delivered as long as possible, possibly in perpetuity. Sediment yield from the catchment, reservoir shape, size and reservoir operation policies are the main factors controlling the rate of reservoir sedimentation. Detailed discussion of these is presented in subsequent sections.

2.0 PRINCIPLES OF RESERVOIR DESIGN FOR SEDIMENTATION

The estimation of sediment yield from river catchments is crucial in reservoir design and computations pertaining to reservoir sedimentation (IS-6518, 1992). The quantity of sediment load reaching to the catchment outlet or reservoir mouth is known as the sediment yield. This is usually expressed tonnes or m^3 per year. The sediment yield per unit catchment area is known as the specific yield. The most common methods of determining the sediment yield are:

(i) From sediment load measurements at a gauging station. Elaborate arrangements for measurement of suspended load and bed load and water discharge at regular time intervals are needed in order to gauge the watershed for sediment yield.

(ii) From surveys of existing reservoirs (CBI&P, 1995). The surveying of the bed profile of reservoirs can be done to determine amount of sediment deposited in the reservoir, assess the annual or seasonal rate and divide it by the trap efficiency to obtain the sediment yield. One is then required to extrapolate these results judiciously to the case of the reservoir under design.

(iii) From use of the empirical relationships which relate the sediment yield with the catchment characteristics and the hydro-meteorological conditions.

(iv) Mathematical modeling of the process of soil erosion in catchment areas can also be used for estimation of the sediment yield.

The empirical method (details given below) may be used for assessment of the sediment yield when time and expense do not permit the adoption of either of the first two methods.

2.1 Empirical Methods of Determination of Sediment Yield

The sediment yield from a catchment mainly depends on the catchment area A_c, the average catchment slope S, the lithology of the catchment, the land use which can be represented by the vegetal cover factor F_c, the drainage density D_d, the annual/seasonal precipitation/ rainfall P, and the storm event or maximum monthly precipitation/rainfall in a year, P_{max} (Garde and Kothyari, 1987).

Some work has been done in India for developing methods for sediment yield estimation. Khosla (1953), Dhruva Narayan and Ram Babu (1983), Garde et al. (1983) and Singh et al. (1990) have analyzed survey data from several small and large reservoirs in India. They determined the amount of deposited sediment from survey data and using the trap efficiency curve of Brune (1953), estimated the sediment yield of different catchments. The yield so determined was analyzed subsequently.

Garde and Kothyari (1987) analyzed data from 50 catchments from different parts of India covering a wide range of pertinent variables. The relationship for average annual sediment yield S_y expressed in cm was proposed by them as

$$S_y = 0.02\,P^{0.60}\,F_c^{1.70}\,S^{0.25}\,D_d^{0.10}\left(\frac{P_{\max}}{P}\right)^{0.19} \tag{2.1}$$

where the erosion factor F_c is

$$F_c = \frac{0.8A_1 + 0.60A_2 + 0.30A_3 + 0.10A_4}{(A_1 + A_2 + A_3 + A_4)} \tag{2.2}$$

Here A_1 is the arable area in the catchment, A_2 is grass and scrub area, A_3 is forest land area and A_4 is the waste land area. Values of A_1, A_2, A_3, A_4 for different catchments were obtained by Garde and Kothyari (1987) from maps given in the National Atlas of India to a scale of 1:6000000, while the drainage density was obtained from maps to scale of 1:1000000. Garde and Kothyari (1987) have also prepared a map of India, (see Fig. 2.1), on which contours of constant sediment yield expressed in Tonnes/km^2-yr are shown. This figure has been used by practitioners to obtain a rapid assessment of the sediment yield in such geographical locations of India for which little or no data on sediment yield were available.

2.2 Mathematical Modelling of Soil Erosion and Sediment Yield Processes

Efforts to predict mathematically the soil erosion due to flow of water and sediment yield of catchments were initiated about five to six decades ago. The development of prediction equations for soil erosion began with analyses such as those by Ellison (1944, 1947). Ellison (1947) presented an analysis of soil erosion sub-processes that formed the basis for more recent soil erosion modeling efforts. Later Meyer and Wischmeier (1969) presented mathematical formulations for detachment and transport by rainfall and runoff the way these processes were hypothesized by Ellison (1947). Kothyari (2008) has presented the current status on the mathematical modelling for soil erosion and sediment yield.

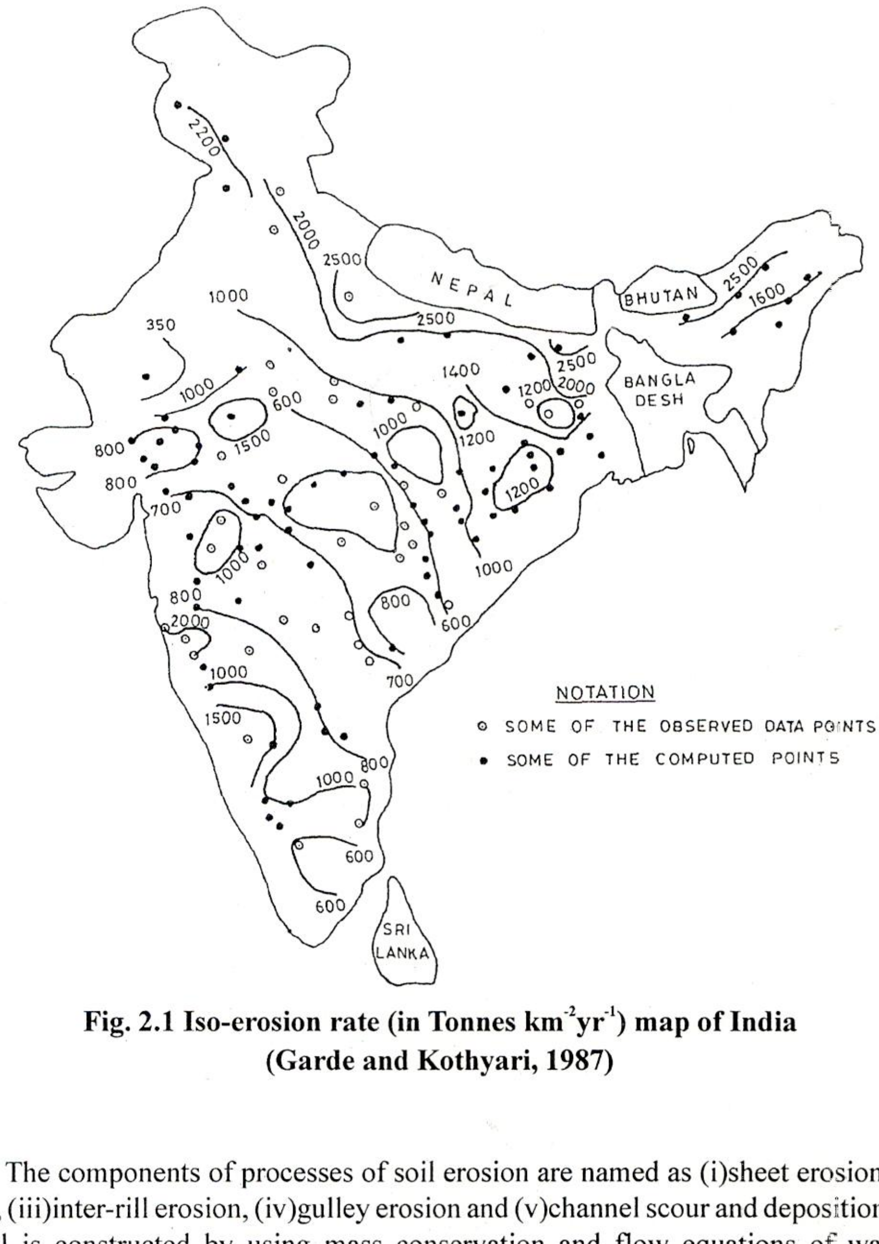


Fig. 2.1 Iso-erosion rate (in Tonnes km^{-2}yr^{-1}) map of India (Garde and Kothyari, 1987)

The components of processes of soil erosion are named as (i)sheet erosion, (ii)rill erosion, (iii)inter-rill erosion, (iv)gulley erosion and (v)channel scour and deposition. When a model is constructed by using mass conservation and flow equations of water and sediment, it is called physically-based or process-based erosion and sediment transport model. For development of these models the ground surface is generally separated into inter-rill and rill erosion areas. Auxiliary equations developed through experimental investigations are used to describe the processes of sediment detachment from rill and inter-rill areas. Transport of eroded sediment to downstream areas is governed by relationships for sediment transport capacity. The transport process connected to the component processes of soil erosion is discussed below.

2.2.1 ***Process of transport of eroded soil :*** When the soil or sediment particles are detached from the ground surface, they become part of the flow and can be transported downstream to distances varying from a few millimeters to many kilometers. This distance is dependent upon the sediment transport capacity of the flow. In many studies on soil erosion the transport rate is expressed in terms of sediment delivery ratio which represents the transported fraction of the total eroded soil. In most of the physically-based models, the transport process and resulting particle sorting effect in rill and inter-rill areas and channel has been considered by the inter-rill detachment relationships. Foster and Meyer (1975) visualized that inter-rill transport capacity is greatly enhanced by raindrop impact. Meyer and Wischmeier (1969) proposed relationship for sediment transport capacity in terms of the discharge rate and land slope. Other relationships which have been utilized for computing transport through inter-rill areas are Duboys (Young and Mutchler, 1969; Foster and Huggins, 1977); Meyer-Peter and Muller (Lee et al., 1997); Yalin (Foster and Meyer, 1972); and Bagnold (Yang, 1972). No single sediment transport equation is said to be superior to others as all these equations require calibration for representing sediment transport by the overland flow within the inter-rill areas (Garde and Ranga Raju, 2006). In many of the present-day mathematical models, the component processes of rill, inter-rill, gulley erosion etc. are simulated by discretising the catchment into sub-areas of relatively homogeneous hydrological characteristics. These models are termed as distributed models. The structure and pattern of results obtained from distributed models are described below.

2.2.1.1 Results of distributed mathematical models for soil erosion and sediment Yield **:**The physically-based distributed mathematical models (Ivanov et al. 2004, Jain et al., 2005), for soil erosion and sediment yield produce results that are distributed in nature. Such models first involve catchment discretization (Fig. 2.2) and the model results are obtained for each of the discretized elements (Fig. 2.3). The results produced by distributed models also help in identification of such areas within the catchment that are vulnerable to soil erosion and which would need priority for implementation of treatment and conservation measures. Details on practices used for conservation soil are presented subsequently in this report.

In spite of the fact that these models are rational and are based on the physics of the processes involved, they are not often used to compute the sediment load from large catchments entering reservoirs, when one is estimating sedimentation in reservoirs. Nevertheless, they are extremely useful in providing guidelines for catchment area treatment to reduce sediment yield.

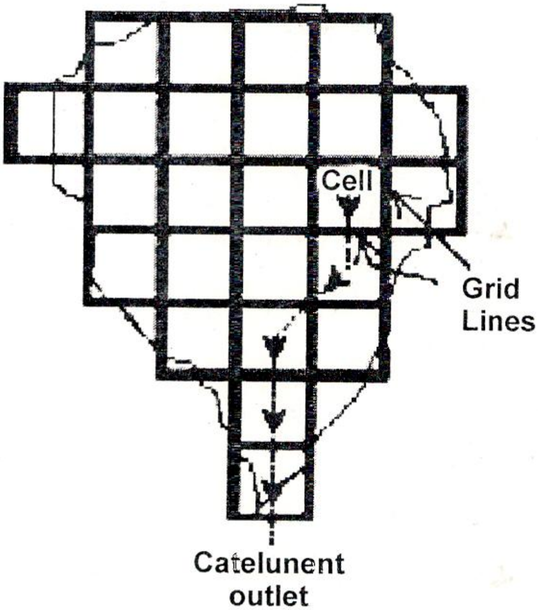


Fig. 2.2 Cell based descretization of a catchment (Jain et al., 2005)

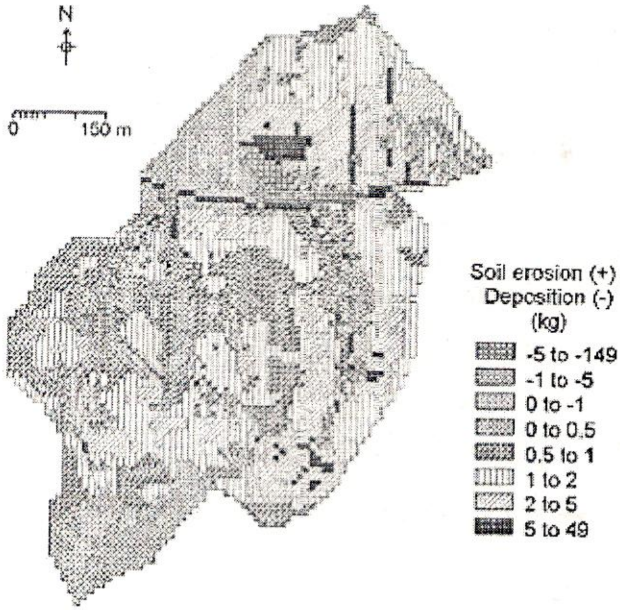


Fig. 2.3 Spatial distribution of soil erosion/deposition in Catsop catchment during the storm event of June 26, 1987 (Jain et al., 2005)

2.3 Trap Efficiency

The ratio of volume of sediment retained by a reservoir to the total inflow volume of sediment to the reservoir over a given period of time, is known as the trap efficiency of the reservoir *TE*, and the same is mostly expressed in percent. Based on field data, trap efficiency is found to be a function of various parameters which include ratio of reservoir capacity to annual inflow *C/I*, retention period defined as reservoir volume divided by daily inflow, sediment and reservoir characteristics, number and position of outlets, and method of reservoir operation. Garde (1995) has presented the status on methods available for determination of trap efficiency and practice used in India for design of reservoirs for sediment management.

Based on the analysis of data from 44 reservoirs in USA with catchment area ranging from 0.098 km^2 to 48,112 km^2, Brune (1953), proposed a curve between trap efficiency *TE* and the *C/I* ratio. Table 2.1 gives a comparison of Brune's trap efficiency values with observations for four Indian reservoirs, which indicates that Brune's method overestimates the *TE* values for two of these reservoirs. Some additional data from reservoirs in India, China and South Africa were used by Garde and Ranga Raju (2006) in developing Fig. 2.4, which is a modified form of Brune's curve.

Table 2.1: Trap Efficiency for a few reservoirs in India (Murthy, 1977)

Reservoir (River)	*C/I*	Period	Trap efficiency (percent)	Brune's estimate of *TE* (percent)
Matatila (Betwa)	0.187	1962-72	67.00	90
Hirakud (Mahanandi)	0.20	1957-73	69-91	90
Gandhisagar (Chambal)	1.80	1962-72	97-100	99
Bhakra (Sutlej)	0.67	1962-73	98-100	96

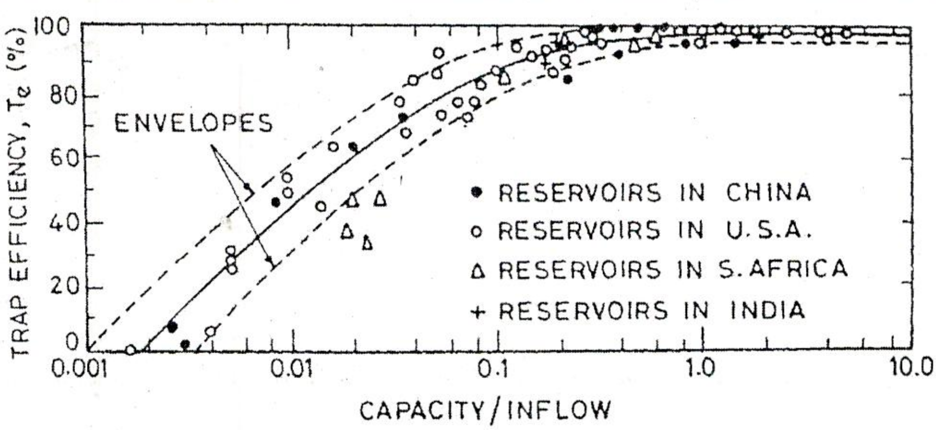


Fig. 2.4 Trap efficiency of storage reservoirs (Garde and Ranga Raju, 2006)

It may be noted that the simple relationship shown in Fig. 2.4 makes no allowance for the size of the transported material. For the same value of C/I, a lower value of *TE* may be expected when the sediment is fine, because some of this material could flow past the dam and not deposit in the reservoir. No account is also taken of the manner of operation of the reservoir; particularly, if sediment is flushed through low-level outlet, *TE* should be lower. Nevertheless, Fig. 2.4 may be used as a guide in the preliminary planning of reservoirs. This figure shows that as time elapses, *TE* decreases on account of decrease of reservoir capacity due to sedimentation.

2.4 Deposition of Sediment

The first hypothesis of the deposition of sediment in reservoirs was given by Lane (1953). He divided the deposits into topset beds, foreset beds, bottomset beds and density current deposits as we move from upstream to downstream; see Fig. 2.5. The size of the deposited material decreases in the downstream direction, the coarsest material being deposited as topset beds, which start where the backwater ends. Density currents may or may not occur in all reservoirs. But in those reservoirs in which they occur and are not flushed out through sluices, density current deposits occur close to the dam.

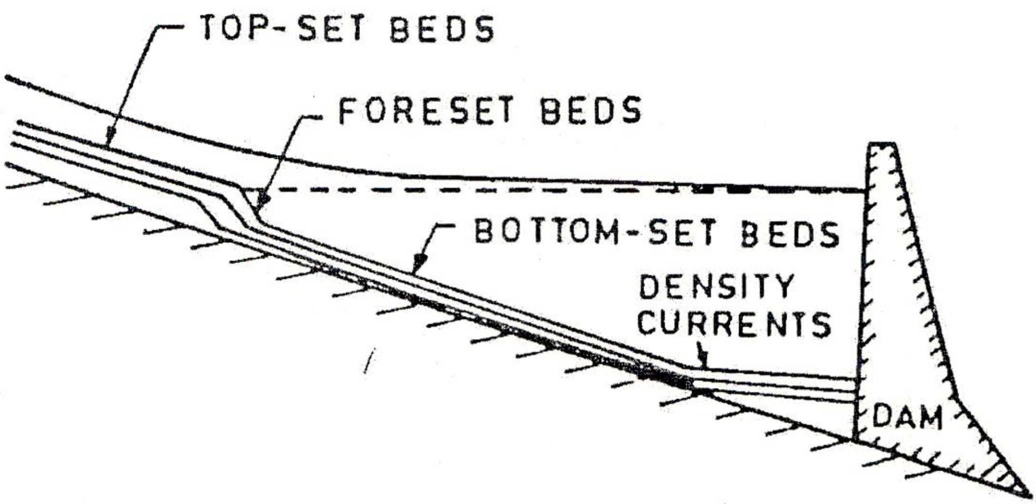


Fig. 2.5 Patterns of sediment deposition in a reservoir (Garde and Ranga Raju, 2006)

The deposition pattern also depends on the manner of variation of the reservoir level and the shape of the valley. Three different types of deposit, viz., Delta-type, Wedge-type and Band-type, have been identified as shown in Fig. 2.6 (Garde and Ranga Raju, 2006). Deltaic deposits occur in reservoirs in which the reservoir level is kept relatively high for a considerable length of time. For gorge-shaped reservoirs in which the storage capacity is small in relation to the incoming load, sediment will soon reach the face of the dam resulting in a wedge-shaped profile. If the water level variation is large, the reservoir is gorge-shaped and the incoming sediment load is small and fine in size, the band-type of deposit occurs.

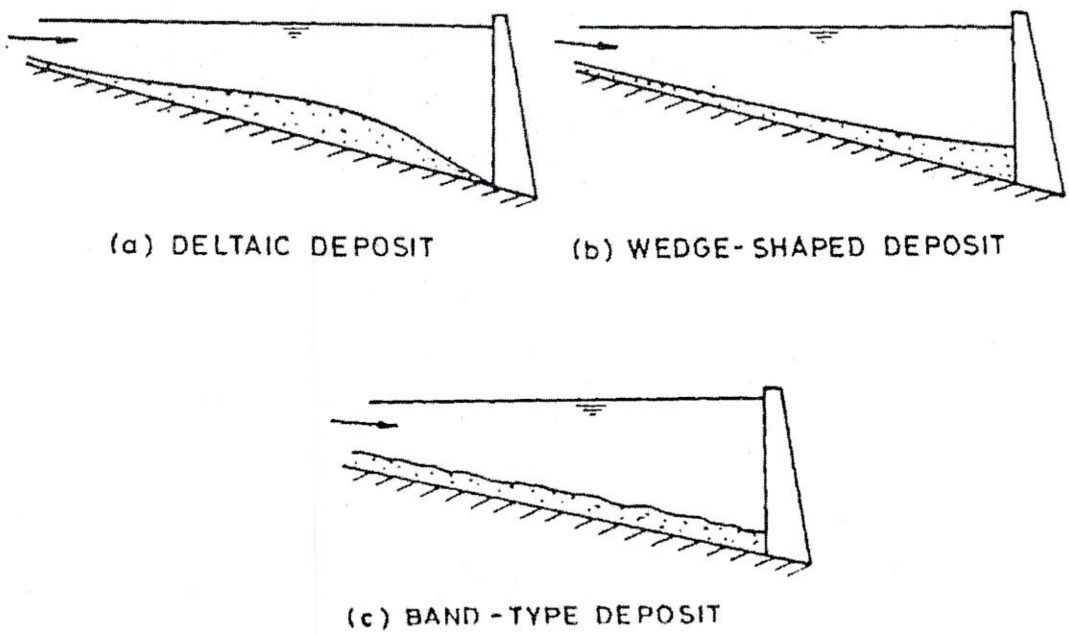


Fig. 2.6 Types of sediment deposition in a reservoir (Garde and Ranga Raju, 2006)

Figures 2.5 and 2.6 provide qualitative illustration of the manner of sedimentation in reservoirs. Estimation of progressive loss in reservoir capacity due to sedimentation requires determination of the extent of deposition at different locations in the reservoir and at various stages in the life of the reservoir. Mention may be made of several empirical methods given during the last five decades for the estimation of the distribution of sediment within the reservoir and for annual loss of capacity: Borland and Miller (1958), Swamee (1974), Murthy (1977 b), Garde et al., (1978) and Garde (1995). Given the purely empirical nature of these relationships and the advances made in the last few decades in the mathematical modelling of sedimentation on the other hand, it is felt that though important from the point of view of historical development the above methods should not be preferred to the more sophisticated methods available today.

2.4.1 Density Current Deposits

Some work has been done in China about deposition of sediments by density currents (Garde and Ranga Raju, 2006). The sediment-laden flow begins to plunge underneath the clear water reservoir at a section where

$$\frac{U_o^2}{\left(\frac{\Delta\gamma_o}{\gamma}\right) g h_o} = 0.60 \tag{2.3}$$

Here U_o and h_o are the velocity and depth of flow at the plunge section, γ is unit weight of sediment-laden flow, and $\Delta\gamma$ the difference in unit weights of sediment-laden flow and water in the reservoir. The density current velocity U' is given by

$$U' = \left(\frac{8\Delta\gamma}{f\gamma} g q' S_o\right)^{1/3} \tag{2.4}$$

where f is Darcy-Weisbach resistance coefficient including the resistance at bottom and interface, q' is discharge of density current per unit width and S_o is stream slope. Based on data from Sanmenxia, Guanting and Hongshan reservoirs in China, the sediment carrying of density currents C_o has been expressed as (Garde, 1995)

$$C_o = 13\left(\frac{U'^3}{gh'\omega}\right)^{0.285} \tag{2.5}$$

where C_o is sediment carrying capacity of the density current in kg/m^3, h' is the depth of the density current, and ω is the settling velocity of sediment particles carried by the density current in cm/s. This equation is valid for C_o values less than 100 kg/m^3. More information is presented on other aspects of density currents in ICOLD (2007) and also in subsequent sections of this report. Little data on density currents in Indian reservoirs is available.

2.5 Empirical Methods of Computation of Sedimentation Profiles

Prior to the advent of mathematical modelling of morphological phenomena and their subsequent application to reservoir sedimentation, several empirical methods were in vogue for thė determination of the sedimentation profiles. The USBR developed the Empirical Area Reduction Method and the Area Increment Method (Borland and Miller, 1958) in 1950s and successfully used them in some of the reservoirs in USA. Annandale (1987) subsequently found that the Empirical Area Reduction method did not yield satisfactory results for several reservoirs in USA even. Garde et al. (1983) gave an empirical method for estimation of sedimentation based on an analysis of data from some Indian reservoirs. But experience with the use of this method subsequent to its publication is limited.

The empirical methods mentioned above or any similar ones for the matter suffer from the following shortcomings:

(i) It is known that sedimentation is initiated where the backwater ends, there being no reduction in velocity upstream of that location. A method which does not explicitly consider the backwater upstream of the dam cannot be deemed to be rational. None of the methods listed above take cognizance of the backwater behind the dam. In other words, the sedimentation calculation is totally divorced from the hydraulics responsible for sedimentation in the first instance.

(ii) The reservoir level varies from maximum water level (MWL) to MDDL minimum drawdown level (MDDL) during the year and this variation affects the sedimentation in the reservoir. This effect is not considered in these methods.

(iii) Most methods consider only the annual load brought in by the river. The pattern of sediment deposition, howèver, is strongly influenced by the variation in water and sediment discharges during the year. Non-consideration of the effects of these variations on sedimentation as is the case in the empirical methods can introduce considerable errors.

(iv) The size of the material deposited along the reservoir bed decreases in the downstream direction, the coarsest material being deposited at the head of the reservoir. Such differential deposition affects the hydraulics of the flow in the next time period and consequently the size and amount of sediment deposited at any location in the next time period. The empirical methods do not consider these effects.

(v) Low-level sluices are being used often recently to prevent some of the incoming sediment from depositing in the reservoir and also for flushing out some of the deposited sediment intermittently. Inasmuch as the empirical methods do not take these features into account, their applicability in cases like these is questionable.

On the other hand, mathematical models-which are described in a later section-do incorporate features to take care of all the aspects mentioned above and are thus popularly used today in preference to the empirical methods.

3.0 MATHEMATICAL MODELLING OF RESERVOIR SEDIMENTATION

Mathematical models have been developed by several investigators for simulation of sediment behavior in general and reservoir sedimentation in particular. All computer based mathematical models for reservoir sedimentation include three major components: water routing; sediment routing and special function modules. Most models include the option of selecting alternative formulae for flow resistance and sediment transport, but none provides the criteria for making the selection. Most models use the finite difference technique to simulate unsteady flow as a series of steady flows. In most equilibrium transport models, the sediment is assumed to reach equilibrium conditions during each computational time step. Different models may produce significantly different results, even when they were run with the same set of inputs. All models are strongly data-dependent and require elaborate data for calibration and verification. But in practice the field data required for this purpose are often not available. The use of all models demands a great deal of professional judgment and field experience for explanation of their outputs (Morris and Fan, 1999). An excellent review on the topic of mathematical modeling for reservoir sedimentation and their assessment is presented by Abood et al. (2009). The present status is described here in brief.

3.1 Numerical Modelling

Numerical models are becoming a useful tool to predict sediment transport and deposition. Numerical models solve the mass transport equation for transported sediment and the mass conservation equation for bed sediment for which the hydraulic field is solved first. The numerical models are briefly reviewed below.

3.1.1 One-dimensional models : One-dimensional mathematical models (1D models) are used to analyze sediment transport along reaches of rivers or in reservoirs where the essential transport processes can be simulated with a one-dimensional flow field. They are applied to problem of sediment accumulation in reservoirs as a function of the operating regime and sediment passing through and over the dams.

One-dimensional models solve the unsteady, cross-sectionally averaged equation for the mass balance of transported sediment which is expressed as:

$$\frac{\partial(Ac_i)}{\partial t}+\frac{\partial(Qc_i)}{\partial x}=\frac{\partial}{\partial x}\left(AD_x\frac{\partial c_1}{\partial x}+S_i\right) \tag{3.1}$$

where

A	=	reservoir/river cross-sectional area
Q	=	discharge
c_i	=	cross-sectionally averaged sediment volume concentration of i^{th} particle size
t	=	time
D	=	dispersion coefficient in the streamwise direction x
S_i	=	source (erosion) and sink (deposition) terms for i^{th} particle size

Most 1D models are mainly designed for non-cohesive sediment transport with the capabilities to only simulate the simple processes pertaining to cohesive sediment transport. These models include HEC-6 and HEC-RAS which were developed by US Army Corps of Engineers (1992), GSTARS 21, GSTARS3 and GSTAR-1D, which were developed by Yang et al. (2005) and MIKE 11 (Garsdal and Christensen, 2006). The EFDCID model that was developed by Hamrick (2001) is also a 1D sediment transport model which simulates settling, deposition and re-suspension of multiple size classes of cohesive and non-cohesive sediments. A bed consolidation model is also implemented in EFDCID to predict time variations of bed depth, void ratio, bulk density and shear strength. UNESCO (2003) has developed a simple model namely, RESCON for the modelling of reservoir sedimentation. The RESSASS model was developed for prediction of reservoir sedimentation by HR Wallingford (HR Wallingford, 1996).

The principal features represented by most of the mathematical models for simulation of reservoir sedimentation are shown in Fig. 3.1. Some of the morphological models which can be used for analyzing sedimentation issues associated with reservoir sedimentation are described below in some detail.

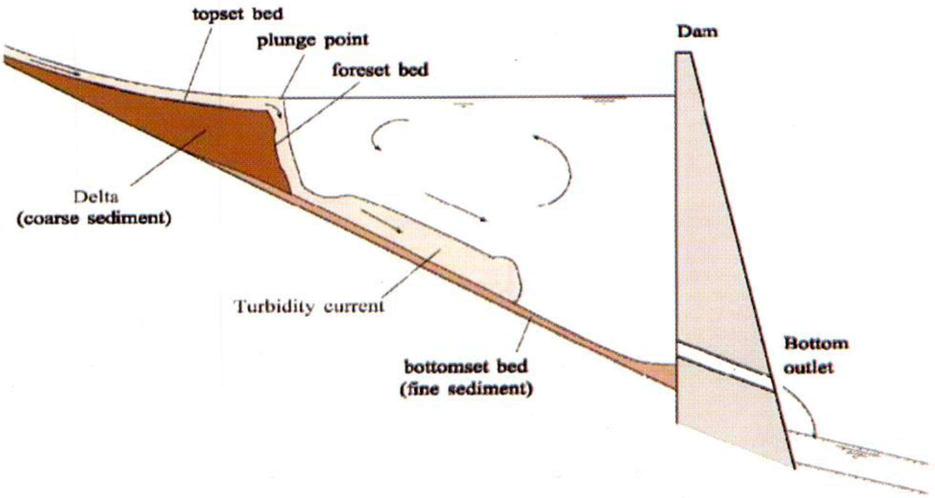


Fig. 3.1 Schematic presentation of the processes involved in simulation of reservoir sedimentation (Sloff, 1997)

HEC-6: HEC-6 is a one-dimensional movable boundary open channel flow model that computes sediment scour and deposition by simulating the interaction between the hydraulics of flow and the rate of sedimentation in the flow. The model has been developed by US Army Croup of Engineers (1992). The model is based on the assumption that equilibrium conditions are achieved between the flow and the bed material transport within each computational time step; such an assumption is made in most other sediment transport models also.

HEC-6 was used by Ranga Raju (2008) to study sedimentation in the Almatti reservoir on the river Krishna. Considering the measured sediment loads and an inflow discharge series for 46 years, backwater and sedimentation calculations were made; the effect of the variations in reservoir levels during this period was also considered. The Ackers White relation was used for the determination of the sediment transport capacity of the coarser fractions of the bed sediment; the criterion for deposition of fine sediment an option available in HEC-6-was used to ascertain the deposition or otherwise of the silt and clay fractions of the sediment. Incidentally, silt and clay fractions formed over 80% of the transported sediment. Table 3.1 shows the change in bed level at different locations upstream of the dam after 46 years of operation of the reservoir for two different FRLs as obtained from the model. Although the above calculations were made after the dam came into operation, the model can very well be used at the planning stage of storage projects to assess the progressive loss of capacity etc.

Table 3.1 Sedimentation in Almatti Reservoir on the River Krishna after 46 years of operation

Sect. No.	Chainage km	Rise/Fall in Bed level(m) for FRL = 519.60 m	Rise/Fall in Bed level(m) for FRL = 524.256 m
0.0 (Dam)	0.00	+0.430	0.0
1.0	6.00	+0.250	0.0
2.0	10.00	+0.162	+0.241
3.0	21.25	-0.015	+0.024
4.0	26.50	+0.165	+0.469
5.0	34.30	-0.012	+0.015
6.0	45.25	+0.146	+0.210
7.0	58.00	+1.644	+0.037
8.0	67.75	+0.031	+0.064
9.0	77.50	-0.226	-0.162
10.0	86.00	-0.329	-0.107
11.0	97.25	-0.265	-0.046
12.0	108.00	-0.043	+0.010
13.0	115.50	+1.915	+2.042
14.0 (Hippargi Barrage)	124.00	+2.818*,+0.162**	+3.173*,+0.777**
2.2	139.20	-0.009	+0.018
3.3	145.60	+0.012	+0.119
4.4	154.24	-0.027	+0.018
5.5	159.20	+0.104	+0.543
6.6	170.00	+0.055	+0.085
7.7	174.80	-0.375	-0.360
8.8	192.40	-0.012	0.0
9.9	202.40	-0.461	-0.433
10.10	216.64	-0.003	0.0
11.11	223.04	+0.116	+0.174
12.12	229.84	-0.390	-0.393
13.13	246.64	-0.451	-0.436
14.14	250.64	-0.262	-0.366
15.15	258.64	-0.424	-0.433

*just downstream of Hippargi Barrage **just upstream of Hippargi Barrage

HEC-RAS: HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system is comprised of a graphical user interface (GUIC), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities (HEC-RAS, 2008).

The HEC-RAS system contains many one-dimensional river analyses including the components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; (3) movable boundary sediment and transport computations. A key element is that all the components use common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.

The version 4.0 of HEC-RAS was updated in March 2008 which supports steady and unsteady flow water surface profile calculations and sediment transport/mobile bed computations simultaneously. Hence this model too is an appropriate tool available for reservoir sedimentation studies.

GSTARS: The General Stream Tube model for Alluvial River Simulation (GSTARS) was developed by the US Bureau of Reclamation (Yang et al., 2005). GTARS is a steady non-uniform flow, one-dimensional model, which simulates certain aspects of two- dimensional flows also by using the stream tube concept for hydraulic computation. This model is also capable of solving for channel width as an unknown variable, based on the concept of stream power minimization.

Hydraulic computations for this model may be made using the Manning's, Darcy-Weisbach, or Chezy's equation and computation can be carried through both subcritical and supercritical flows without interruption. Geometry is specified by channel cross sections and roughness coefficients are specified as a function of distance across the channel.

In GSTARS the sediment load is computed for each size class individually as if the entire bed consisted of that size. The resulting load is multiplied by the fraction of bed material corresponding to that particle size to give the bed material load for each size class. This model, however, does not simulate the scour and deposition of silts and clays.

FLUVIAL: FLUVIAL model is a one-dimensional model developed by Chang (1984) and it is used to analyze reservoir sedimentation. This model contains five major components: hydraulic routing, sediment routing, change in channel width, change in channel bed profile and change in transverse bed geometry due to curvature. A particular feature of this model is the ability to simulate the development of the transverse bed slope in a curved reach.

Model geometry is specified by a series of cross sections. Bed material composition is specified at the upstream and downstream boundaries of the model and may be specified at other locations as well. Hydraulics, sediment transport and bed and width adjustment are simulated iteratively. Hydraulic routing can be performed as a series of steady approximations by the computationally faster standard step method, or as dynamic wave unsteady flow modelling. Bed roughness can be input in the form of Manning's values to predict alluvial bed roughness. Six different sediment transport formulae are incorporated into the model and armoring computations are performed as well. This model also does not simulate silts and clays.

RESSASS: RESSASS numerical model is a one-dimensional, uncoupled model, capable of simulating the reservoir sedimentation due to transport of alluvial material as well as silt and clay. The equations of continuity and momentum for flow as well as the continuity equation for sediment transport are solved using the finite difference technique.

The hydraulic calculations are based on steady-state backwater computations and sediment transport calculations are carried out for a range of sediment sizes. The flow and sediment transport simulations are one-dimensional. Thus only variations along the length of the reservoir are considered and all the quantities calculated are averaged over the cross-section. However, the user defined functions specify the distribution of sediment deposition across a section. RESSASS model can be operated in one of the following two modes: (i) Reservoir levels at the dam (at set time intervals) are used with reservoir inflows to calculate spillway outflows. Discrepancies between the known water level changes and those expected from the differences between and outflow are recorded during the run. (ii) When reservoir levels are not known, the numerical model calculates them from reservoir inflows and releases.

Predicted reservoir bed cross sections at the end of a simulation period can be used as the input conditions for a subsequent period of simulation. Studies on sedimentation in a few Indian reservoirs were conducted at Roorkee some years ago by the authors using the RESSASS software. Adequately satisfactory simulation of the sedimentation deposition pattern along the reservoir bed as well as across the reservoir width could be achieved in most of the cases as illustrated by Fig. 3.2.

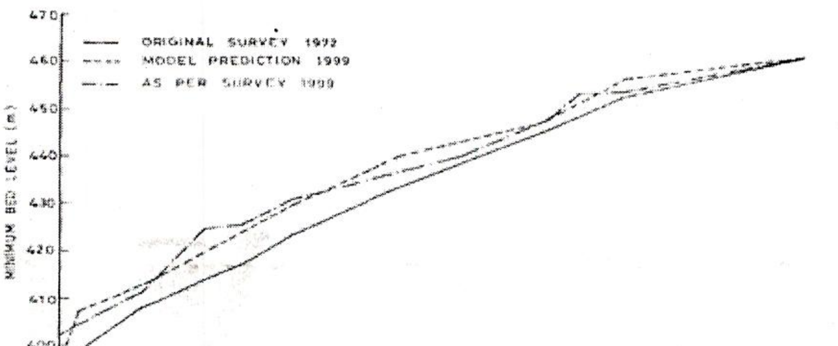


Fig. 3.2 Results from reservoir sedimentation modeling for Konar reservoir by using RESSASS model (Ranga Raju et al., 1997)

MIKE 11: Developed by DHI, Denmark, MIKE 11 is a one-dimensional coupled morphological model with the capability of being applied for a variety of alluvial river problems including reservoir sedimentation. The model has been used successfully in several projects in India and abroad. The model can handle both cohesive and cohesionless sediments. The results obtained by using this model in the case of the Baglihar dam on the Chenab river in India are discussed later.

3.1.2 Two-dimensional (2D) models: Since the 1990s, there has been a development in computational research towards the 2D models. Most of the 2D models have the capability that make them user-friendly and popular because of the easy data input and visualization of results. 2D models can provide spatially varied information about water depth and bed elevation within rivers, lakes and estuaries.

Two-dimensional models solve the depth-averaged or width-averaged convection-diffusion equation with appropriate boundary conditions. Usually, three types of boundary conditions are encountered in a 2D numerical model; (i) at the inlet boundary, the sediment concentration is given, (ii) at the outlet boundary, there is no concentration gradient. (iii) at solid boundaries, there is no horizontal flux normal to the solid surface.

Two-dimensional models have been applied to channel sedimentation and harbor sedimentation studies, where the variation of flow parameters with depth or width are mostly neglected. The 2 D models in vogue include the following:

TABS-2: A group of finite element based hydrodynamic and sediment transport computer code developed by USACE Waterway Experimental Station (Thomas and MCAnally 1985).

MOBED-2: A finite-difference hydrodynamic and sediment transport model used in a curvilinear coordinate system, developed by Spasojevic and Holly (1990). The model can simulate water flow, sediment transport and bed evolution in natural waterways such as reservoirs.

USTARS: This model is a modified form of GSTARS that is also based on the stream tube concept (Lee et al., 1997). The hydrodynamic and sediment equations are solved with a finite-difference scheme in a rectilinear coordinate system. As in GSTARS, the theory of minimum stream power is used here to determine the optimum channel width and geometry for a given set of hydraulic, geomorphologic, sediment and man-made constraints.

ADCIRC-2D: A finite-element hydrodynamic and sediment transport model developed by Luettich et al. (2004) in a rectilinear coordinate system for simulating large-scale domains by using 2D equations for the external mode but using the internal mode for obtaining detailed velocity and stress at localized areas.

MIKE 21C: The 2-D model MIKE 21C (DHI, 2006) developed by DHI, Denmark is an integrated river morphology modelling tool which can simulate changes in the river bed and plan form including bank erosion, scouring, shoaling associated with, for instance, construction work and changes in hydraulic regime. The results obtained from this model in the region immediate upstream of the low-level sluices of the Baglihar dam are discussed later.

3.1.3 ***Three-dimensional (3D) models:*** In many hydraulic engineering applications, one has to resort to 3D models when 2D models are not suitable for describing certain hydrodynamic/sediment transport processes. Flows in the vicinity of outlets (under- sluices) and near hydraulic structures are examples in which 3D flow structures are ubiquitous and in which 2D models do not adequately represent the physics. 3D models solve the full convection-diffusion equation, with appropriate boundary conditions.

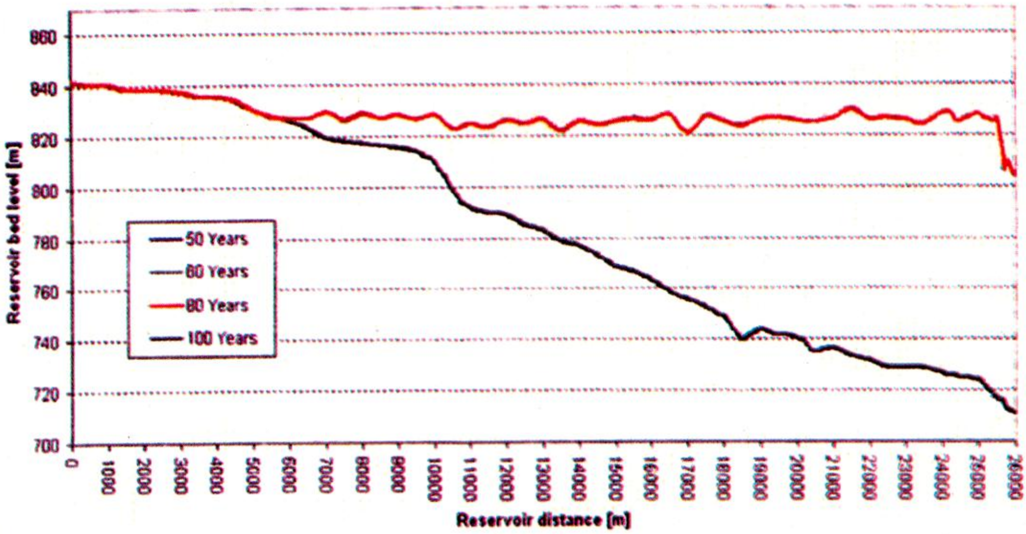
A general 3D sediment transport model was developed in China by Fang and Wang (2000). This is a sophisticated model that uses the equation for sediment-laden water with variable density, meaning the model can take account of stratified flow, which is the case in most Chinese rivers.

The US Army Corps of Engineers developed a 3D sediment transport model, CH3D-WES, that solves the complete 3D advection-dispersion equation using a finite-difference method (Athanasion et al., 2008). The model solves the 3D, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable density fluid. Other 3D models such as SSIIM, which is a finite volume hydrodynamic and sediment transport model is based on an unstructured grid system (Olsen, 1994). It is a general three-dimensional sediment transport model. Although not developed for reservoir sedimentation, the model was used for this objective. The SSIIM model was used by Olsen (1994) to simulate deposition pattern in two reservoirs in Costa Rica and a reservoir in Thailand. For the Thai reservoir, the author stated that due to unavailability of field data a direct comparison between the calculated results and the field data could not be made.

DHI (2006) also have developed a three-dimensional model called NS3, which provides a detailed flow and sediment transport pattern, and can be used to predict initial erosion rates in 3D flow fields.

The Baglihar dam on the Chenab river in India is a 130 m high concrete dam in which low-level sluices are provided for passing floods as well as some of the incoming sediment load. The sluices are intended to provide a favorable environment (from the point of view of sediment entry) near the power intake located a little upstream of the sluices. Garsdal and Christensen (2006) used NS3 in the vicinity of the intake in combination with MIKE11 further upstream to compute the reservoir bed levels in the near-field (close to the sluices) as well as in the far-field (well upstream of the sluices). Figure 3.3(a) shows the bed profile over the entire length of the reservoir after several years of operation. The dam is located at chainage of 26000 m and the elevation of the sill of the sluices is 808 m. Figure 3.3(b) shows the bed profile to a larger scale for a distance of about 2000 m from the sluices.

The results show clearly the efficacy of the sluices in keeping the bed levels low (805 m to 810 m) over a distance of about 400 m in from the dam. This is significant when one considers that the sill of the power intake located in this region is at 818 m and thus the bed level near the intake is about 10 m lower than the sill level of the intake.



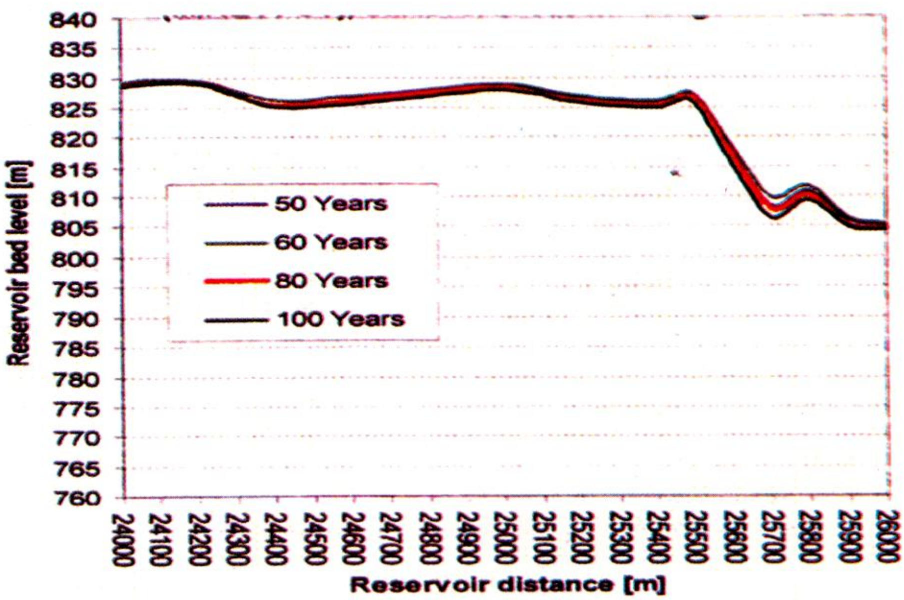


Fig. 3.3 Sedimentation profiles upstream of Baglihar dam computed using MIKE-11 and NS-3 with sluice spillway in operation (Garsdal and Christensen, 2006)

The 2-D DHI model MIKE 21C has also been used (Govt. of India, 2006) to study the bed profile near the low-level sluices of the Baglihar dam. A huge deposit was introduced artificially upstream of the sluices and the effect of operation of the sluice for a period of a few days on this deposit was studied using MIKE 21C. Figure3.4 (a) & (b) shows clearly that the deposit has been washed away upto about 200 m from the dam. A study of this nature thus provides clear proof as to the effectiveness of the sluices in maintaining a favorable sediment environment near the power intakes located immediately upstream of the sluices. The plan view of the scoured bed in the vicinity of the sluices and the intake is shown in Fig. 3.4(b).

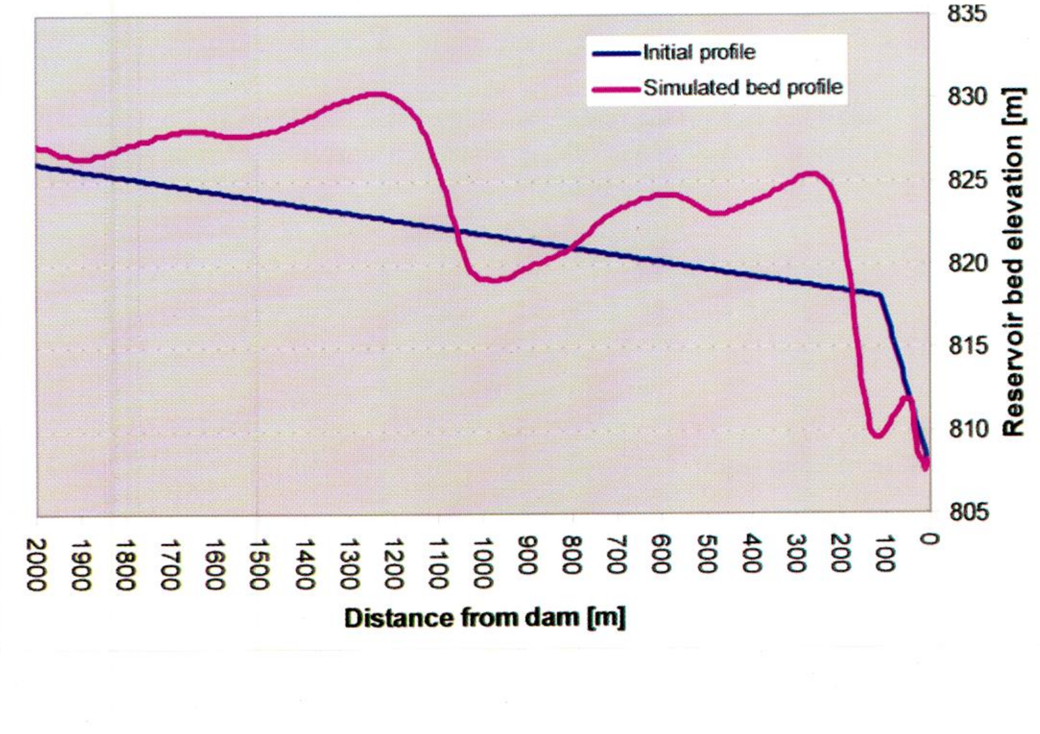


Fig. 3.4(a) Development in bed profile in Baglihar reservoir as predicted by MIKE-21C (Govt. of India, 2006)

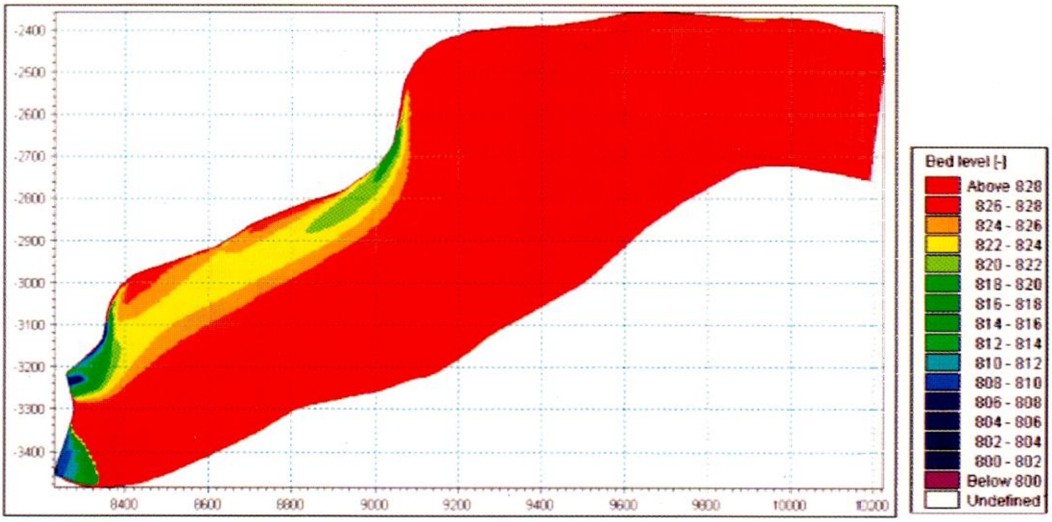


Fig. 3.4(b)Plan view of the reach upstream of sluice spillway of Baglihar dam showing development of deep channel near spillway and power intake (Govt. of India, 2006)

3.2 Sediment Load Input

The sediment load carried by the river at the upstream end of the modelling reach needs to be provided as an input in all mathematical models. The accuracy of the results obtained is strongly dependent on the correctness or otherwise of this load. It is advocated that sediment measurements made on the river be used for this purpose in preference to any empirical method. Inasmuch as the investigation and planning of reservoir projects takes 5 to10 years at least, it should be possible to install gauging sites for daily measurement of the sediment load carried by the river and provide sediment data covering a period of at least a few years, which can be used in the model. It would also be possible to make a proper choice of the sediment transport relation to be used in the model on the basis of these data. With a properly chosen transport relation, the model should indicate equilibrium conditions (i.e. no change in bed levels) over a period of time for the sediment and the discharge hydrographs obtained from measurements inputted at the upstream boundary.

3.3 Data for Calibration of Mathematical Models

It is desirable that mathematical models are calibrated using the data for the reservoir in question before they are used to make long-term predictions of the sedimentation in the reservoir. It is thus common practice to conduct surveys on reservoir sedimentation at intervals of a few years after the reservoir comes into operation. The common practice is to use echo sounders mounted on fast moving boats to determine the water depth at several locations in the reservoir. The location of the measuring station itself is ascertained through a global positioning system (GPS) receiver. With the use of high-speed boats and automatic data-recording equipment it is possible to survey even large reservoirs in about 4-6 weeks using this method. Comparison of the depths at the time of survey with those at the time of impoundment gives the depth of deposit.

3.4 Remote Sensing Applications for Reservoir Sedimentation

Remote sensing is being used in recent times for carrying out reservoir sedimentation surveys. The basic principle of remote sensing method is as follows: In the visible region of the electromagnetic spectrum (0.4 - 0.7 μm), the transmittance of water is significant and the absorptance and reflectance are low. 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. Such reflectance characteristics of the water surface helps in detecting the spread of reservoir water surface. However, due to transmittance of visible radiation through water, if water depth is shallow, the radiation is reflected by the bottom of the water body, transmitted through water and detected by the sensor. In such situations, it may not be clear from the visible bands whether there is a thin water layer above ground surface. To resolve this, the image in the NIR band must be inspected. In the NIR band, water apparently acts as a black body absorber and the boundary between the water and other surface features is quite prominent.

Due to deposition of sediments, the reservoir water spread area at various elevations goes on reducing. Most reservoirs have annual drawdown and refill cycles. A series of satellite imageries covering a wide range of reservoir water levels are obtained. These imageries are analysed to determine the water spread area of the reservoir at the time of satellite overpass. The actual water surface elevation in the reservoir at the time of satellite pass can be obtained from the dam authorities. 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 such a table with a previous table yields the capacity lost during the intervening period.

Remote sensing approach has the following advantages:

- Satellite data through its spatial, spectral, and temporal attributes, can provide synoptic, repetitive and timely information regarding the revised water spread area in a reservoir.
- By using the digital analysis techniques and GIS in conjunction, the sediment deposition pattern in a reservoir can be determined.
- Remote sensing approach is highly cost effective, easy to use and requires little time for analysis as compared to conventional methods.
- Sedimentation can be easily assessed in reservoirs that are located in areas that are difficult to access.

There are however, some limitations of the remote sensing approach as listed below:

- The amount of sediment 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.
- Presence of clouds poses a problem in correctly demarcating the reservoir water spread area and hence sedimentation. Difficulties are also encountered if the turbidity of the reservoir water is high.
- This technique is not suitable for reservoirs that are located in narrow valleys with steep slopes.
- Most importantly the remote sensing method can only be used for assessing the extent of deposition in the existing reservoir. It cannot be used for reservoir design against possible sedimentation at the planning stage.

Data from several reservoirs in India have been analyzed by the research groups from National Institute of Hydrology, Roorkee for determination of the extent of sediment deposition in some reservoirs (Goel et al., 2002, Jain et al. 2002 and Rathore et al., 2006). These include: Nagarjunasagar, Hirakud, Gandhinagar, Tungabhadra, Linganamakki, Tawa, Ramganga, Ghatprabha, Matatila, Somasila, Lower Manair, Barna, Vaigai, Upper Kolab, Ravi Shanker Sagar, Lower Bhawani, Singur, Bhakra, Nizamsagar, and Tandula (Sharad K. Jain *personal communication*).

4.0 SEDIMENT MANAGEMENT

As mentioned previously, the last century was concerned with reservoir development. However, the 21st Century will need to focus on sediment management for deriving full benefits from the existing and new reservoirs. The possible measures for sediment management are discussed herein.

4.1 Measures for Reduction of Reservoir Sedimentation

The rate of sedimentation in a reservoir can be controlled by adopting measures which follow one or more of the following principles.

(i) Control of sediment inflow to reservoir

(ii) Control of sediment deposition in reservoir

(iii) Removal of sediment deposits from the reservoir

Various measures for controlling the sedimentation of reservoirs that are in vogue can be classified as

- Management and treatment of river/reservoir catchment or watershed
- Measures for bypassing the sediment-laden inflows
- Flushing/sluicing of the reservoirs and venting out the density currents
- Dredging and excavation

All the above measures of sediment management and control are applicable to storage type reservoirs as well as to run-of-the river type projects. The sediment management practices applicable only to run-of-the reservoir projects, however, are separately discussed subsequently in brief.

4.1.1 Watershed management and treatment :

The watershed management programme consists of adopting soil conservation practices to reduce the sediment yield from the river catchment. The rate of sediment deposition in reservoirs is greatly dependent on the sediment yield of the catchment. The primary benefits of soil conservation measures are reduction in sediment yield of coarse sediments like gravel and boulders - these being the sizes more difficult to eject once deposited inside the body of the reservoir. It is difficult to control the yield from catchment of fine sized sediment like clay, silt and sand. However, such fine sediments tend to deposit near the dam body and can be flushed out through reservoir operations under certain circumstances.

Watershed management practices can be broadly classified as:

(i) Use of structural measures for soil conservation

(ii) Use of Biological measures for soil conservation

(iii) Combination of the above measures

(i) *Structural measures*

Structural measures consist of building check dams, plugging of the gullies, building the landslide control structures, and river training and protection works. These measures generally entail large cost and are, therefore, implemented infrequently as a means for reduction of sediment yield from the catchment. However, these measures have been highly successful in local control of the problems of sediment generation and shifting of rivulets and river courses. Structural measures such as check dams etc. have been highly effective in reducing sediment yield from smaller size catchments having areas less than about 25 km^2. However, they become highly uneconomical and are also less effective in reducing the sediment yield from larger size catchments. The main reason for this is that coarse size debris generating in head water catchments gets deposited in the check dams and is retained there. In lower reaches the sediment moving through rivers is having relatively smaller size which does not deposit in smaller size settling basins as check dams. Also additional sediment gets generated due to the process of re-mobilization of previously deposited sediment in river courses and along river bed and banks. The erosion from river bed and banks is dominant in the larger size catchments which nullifies the effect of soil conservation measures adopted within the catchment area (Hadley et al., 1985).

(ii) *Biological measures for watershed management*

The biological measures of catchment area treatment mainly include afforestation measures and use of land terracing, vegetation strips etc.

The vegetation grown over land surface is expected to protect the soil against the action of overland flow and rainfall. The rate of soil erosion and hence the sediment yield is expected to be less from the vegetated land surfaces. This practice of soil conservation is often recommended by environmentalists. Large numbers of researchers (Hadley et al., 1985), however, have reported that activities such as landslides, which result in an enormous increase in sediment yield from catchments frequently occur even in densely forested land slopes. The activity of mass wasting or landslides is more controlled by lithological factors rather than by the land cover alone and hence it is difficult to control these merely by plantations or covering the land slopes with vegetation. Kothyari et al. (2009) have also demonstrated the transport rate of sediment to be fairly large even from vegetated channel surfaces.

Similar to the case of structural measures for reduction of sediment yield in which mostly coarser size fractions of the sediment are reported to be controlled, the biological measures too are able to reduce the sediment yield of boulders and gravel. These measures too are beneficial in the sense that if deposited within the reservoir, flushing out or ejection of coarse sediments such as boulders is very difficult. The yield of fine size sediments like clay and silt is seldom reduced even by afforestation. Nevertheless, as already mentioned the practice of reservoir flushing or sluicing (details given subsequently) is effective in reducing the extent of reservoir sedimentation caused due to deposition of fine sediments, as such sediments are mostly deposited near the dam body. The biological measures too have been observed to be effective in reducing the sedimentation in reservoirs on rivers not having large size of catchment area. The biological measures are quoted to be effective when the catchment area is smaller than about 100 km^2 (ICOLD, 1989, 1999).

(iii) *Combination measures*

In several cases the combination of both structural measures and biological measures has been adopted for controlling reservoir sedimentation. As per Asthana (2007), for catchments having area less than about 25 km^2, soil conservation practices if implemented in combination, greatly reduce erosion from land surface, bank cutting and head cutting, However, in catchments having areas upto 250 km^2, a reduction of 80% in sediment yield is possible by adopting the combination measures of slope stabilization, land afforestation, check dams and river bank stabilization.

4.1.2 Prioritisation of areas for application of soil conservation measures

The implementation of measures for soil conservation requires huge investment. The cost of implementation of conservation measures increases greatly as the area of the catchment required to be treated increases. The prioritization of the areas within the catchment for treatment thus becomes an issue in this context. The distributed mathematical modeling for soil erosion and sediment yield helps in selecting the areas to be treated for soil conservation on priority. The details on distributed modelling for soil erosion were given in Section 2. Figure 4.1 shows the results from a distributed model which depicts the land zones within the catchment areas identified through mathematical modelling to be vulnerable to soil erosion and which may need to be treated with priority.

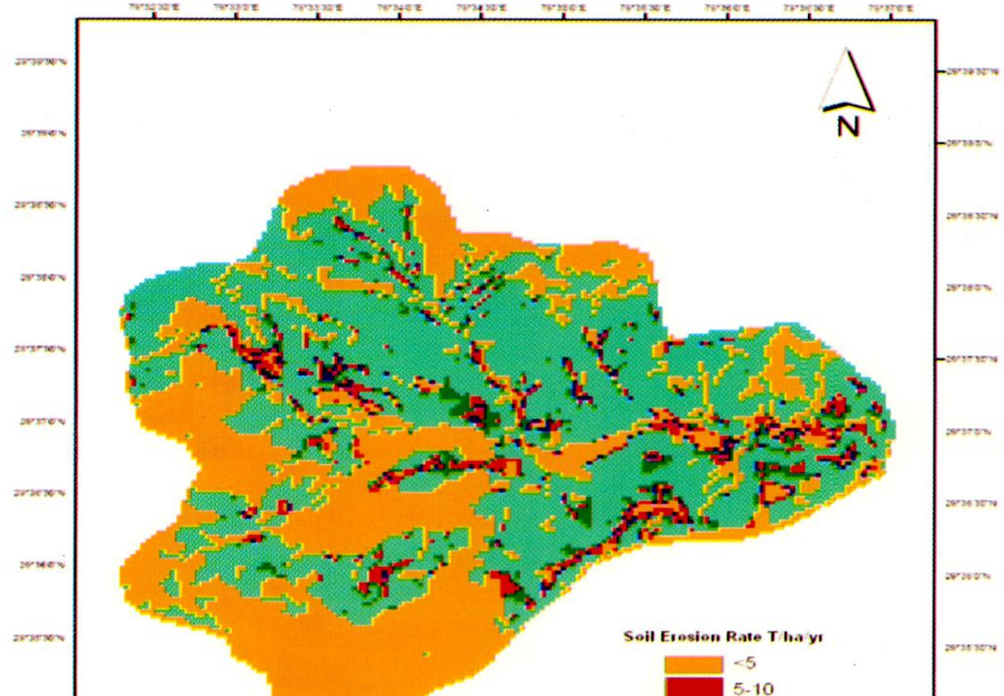


Fig. 4.1 Map of Khulgad catchment, Uttarakhand showing areas vulnerable for soil erosion (Ramsankaran et al., 2009)

4.2 Effects of Measures for Reduction of Reservoir Sedimentation

Several case studies on effect of soil conservation measures on reduction of sediment yield are presented by Asthana (2007). Results of various conservation measures on sediment yield from relatively large size catchments is presented in Table 4.1. It can be seen from Table 4.1 that in some cases the soil conservation measures resulted in substantial reduction in sediment production rate (SPR) but in many other cases the impact of these measures was marginal. The data in Table 4.1 show a reduction of 68% in SPR of Tungabhadra reservoir. This reduction, is however, also the result of constructing a number of dams and weirs in the catchment along with the adoption of biological measures for soil conservation. After the construction of the Tungabhadra dam in 1953, a high weir across the Tunga river was built in 1957, the Bhadra dam was built in 1963 and the Hagaribommanahalli dam was built in 1970. Soil conservation measures like contour bunding in an area of 2085 km^2 and afforestation works in an area of 223 km^2 were started in 1962-63 within the catchment of the Tungbhadra and the 1972 survey of the reservoir showed a reduction in SPR by 68.2%, in this catchment (Rajan, 1982).

Table 4.1 : Sediment production rate (SPR) for catchments of different rivers (Asthana, 2007)

	Catchment (State)												
River catchment →	Chambal (MP+Raj)	Maithon (Bihar)	Panchaet (Bihar +WB)	Hirakud (MP+ Orissa)	Kangsbati (WB)	Lower Bhavani (TN)	Muchkund Sileru (AP + Orissa)	Matatilla (MP+UP)	Nizam-sagar (AP+ KTK+ MAH)	Ramganga (UP)	Sutlej (H.P.+ Punjab)	Tawa (MP)	Tunga-bhadra (KTK)
Total area (Lac ha)	26.00	12.48	5.71	82.20	3.79	2.80	5.02	21.06	21.69	3.63	18.20	5.98	28.28
Priority area (Lac ha)	12.61	5.14	0.13	25.34	1.52	0.91	1.79	8.26	6.39	1.04	5.54	2.71	8.61
Treated area upto Vth Plan (Lac ha)	2.07	2.30	0.06	2.10	0.49	0.05	0.64	0.36	0.13	0.44	1.31	0.06	1.36
%Priority area treated	16.41	44.75	48.15	8.29	32.24	5.50	37.65	4.36	2.03	42.31	23.65	2.84	15.79
Year of starting	1961-62	1961-62	1961-62	1961-62	1963-64	1969-70	1961-62	1969-70	1961-62	1961-62	1975-76	1975-76	1962-63
Assumed SPR	3.60	1.60	2.50	2.50	3.30	N.A.	3.9	1.30	0.30	4.30	4.29	3.60	4.30
First observed (i) Survey year	1952	1963	1962	1964	1967	1965	1950	1964	1965	1958	1962	1977	1963
(ii) SPR	6.19	15.27	13.16	4.91	5.86	4.32	3.38	5.25	6.91	18.59	8.04	6.25	18.85
Second Observed (i) Survey year	1976	1979	1976	1977	1972	1974	1978	1974	1973	1974	1975	1980	1972
(ii) SPR	5.29	12.39	10.48	3.58	2.16	3.89	2.19	3.82	6.34	17.30	5.95	2.67	6.0
%Reduction in SPR (between two surveys)	14.50	18.86	20.36	27.10	63.10	14.60	35.20	27.70	8.20	6.90	26.00	49.10	68.20

MP: Madhya Pradesh, Raj: Rajasthan, WB: West Bengal, TN: Tamilnadu, AP: Andhra Pradesh, UP: Uttar Pradesh, HP: Himachal Prade sh, KTK: Karnataka, SPR: in ha.m./100 km^2/year

Success in reducing SPR at Guanting Reservoir, China on Yongding river has been reported (Fan, 1986). The reservoir with a capacity of 2290 Mm^3 was completed in 1956. It showed average rate of silting of 70 Mm^3 per year during 1956-60. In 1958 measures were adopted in the catchment to reduce the SPR. Three hundred small and medium reservoirs with total capacity of 15 Mm^3 were built on the tributaries and main river in the upstream, as well as other soil conservation measures and works for diversion of silt-laden flow for agriculture were adopted. These resulted in reduction of SPR to 6.6 Mm^3 in the year 1980.

Mangla reservoir on the river Jhelum in Pakistan was built for a storage capacity of 9470 Mm^3. A 30-year project of soil conservation measures was started in 1959 to reduce the sediment yield. It consisted of large number of structural and non-structural measures in an erosion-susceptible area of 7.64 km^2. The total catchment area of the river Jhelum upto Mangla dam is 3330 km^2. However, the subsequent survey showed insignificant impact of these measures and the anticipated reduction of 30% was not achieved (Mahmood, 1987). However, intensive plantation of salt cadar, Tamarisk tree (Tamarix gallica) in the upstream parts of reservoir of lake McMillian and Elephant Butte reservoirs in USA, produced reasonably good results on reduction of sediment yield (Fan, 1986). The effect of 4 km wide vegetative screen provided on upstream of Hongshan reservoir having capacity of 2500 Mm^3 in China also produced similar results (Qian, 1982).

4.3 Measures for Bypassing the Sediment-Laden Inflows

The concept of bypassing the sediment-laden inflows before entering the reservoir is more frequently utilized for separating silt from inflows to irrigation canals and flows to the power channels. This measure for reduction of reservoir sedimentation has limited application, particularly in Indian conditions as the catchment areas of reservoirs are relatively large. Bypassing the sediment-laden inflow by tunnels to the downstream of the intake for Nathpa-Jhakari power station on the Sutlej river in the state of Himachal Pradesh in India, has, however, been recommended for use recently to prevent the frequent closure of this power station due to silt problems. This proposal however, is yet to be implemented.

Asthana (2007) has listed some examples on bypassing sediment-laden flows before entering into the reservoir and these are briefly described below.

The line diagram of the layout of the open channel for bypassing sediment-laden flow from the river Colorado to All-American canal scheme is shown in Fig. 4.2 (Batuca and Jordaan, 2000). A discharge of 340 m^3/s is diverted into this canal and the diverted flow is used to meet irrigation demand. The remaining part of the river flow enters the Laguna reservoir. As a result of bypassing of flow into the canal, the Laguna reservoir and the Pilot Knob hydropower plant are practically free from silt problems. The All-American canal is provided with a comprehensive mechanized arrangement of desilting at its head.

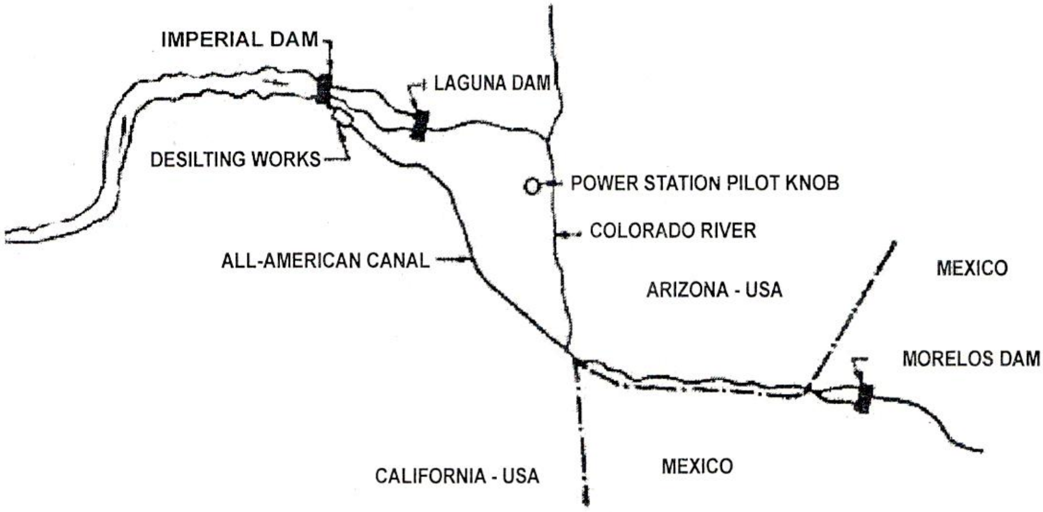


Fig. 4.2 The All-American canal from river Colorado, USA (Batuca and Jordaan, 2000)

Another example of sediment bypass around a reservoir is at Nagle reservoir having a capacity of 23.2 Mm^3 formed by a 52 m high concrete gravity dam on Mgeni river in Natal Province of South Africa (Batuca and Jordaan, 2000). This reservoir is located on a horseshoe bend of the river and the floods are bypassed through a channel across the bend. A weir at the upstream end of the reservoir diverts the flood to the bypass channel (Fig. 4.3). Discharges upto 2000 m^3/sec are bypassed through the channel and the reservoir has insignificant siltation since its completion in 1950.

The concept of bypassing through canals has been adopted successfully at several projects in other countries specially in China (Asthana 2007). Hushan, Shiya, Yang-Shuigon, Lushuite reservoirs are reported (ICOLD, 1999) as examples of bypassing sediment from inflows. Bypassing of sediment-laden inflows by tunnels/ galleries/ conduits has also been practised on small reservoirs in Switzerland, Japan, Italy, Austria and South Africa. The layout of bypassing at Amsteg reservoir in Switzerland is given in Fig. 4.4. However, in case of the Palagnedra dam reservoir in Switzerland, the bypassing gallery of 225 m^3/sec capacity was found to be ineffective during a high catastrophic flood. In the Miwa reservoir Japan, the bypassing of sediment-laden inflow is done alongwith other methods of sediment interception and removal (Batuca and Jordaan, 2000). At present there are no examples in India on use of bypassing the sediment-laden inflows except for the one planned in case of the Nathpa-Jhakari project.

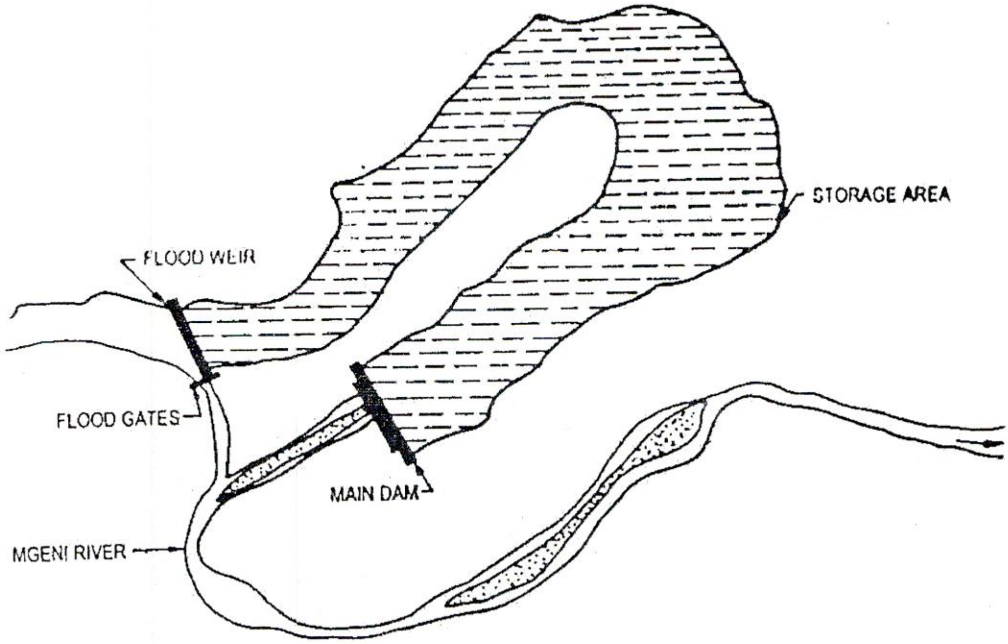


Fig. 4.3 Sediment bypass arrangement at Nagle reservoir, SA
(Batuca and Jordaan, 2000)

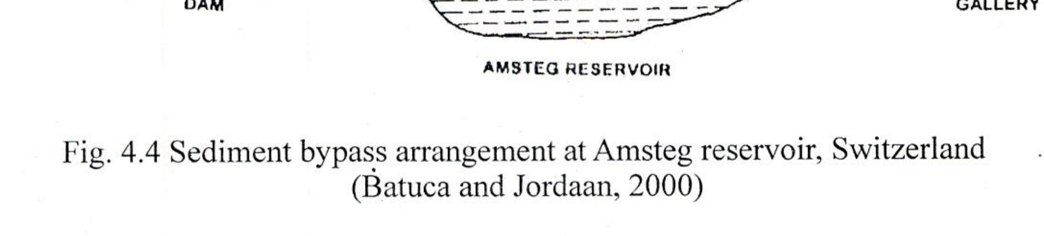


Fig. 4.4 Sediment bypass arrangement at Amsteg reservoir, Switzerland
(Batuca and Jordaan, 2000)

4.4 Concept of Integrated Sediment Water management

Early. experience with low-level sluice gates for flushing out sediment from reservoirs was not very satisfactory primarily because relatively small-sized gates were used. Such gates (say less than 4.0 m × 4.0 m) have limited zone of influence and tend to get choked fequently. Their vulnerability to choking increases in the event of a sudden sediment rush due to landslides etc. and there is also the possibility of large boulders or trees brought in submerged conditions blocking the openings. Moreover, it is difficult to handle the problems of cavitation in small-sized sluices, as chances of choking of air entry from the downstream end are more. The structural provisions needed for aeration are large in comparison to their size, which make their provision difficult.

Practically none of the above difficulties is encountered when one uses large-sized sluice gates. The use of large-sized low-level sluice spillways for handling large floods is extremely popular today and has the great advantage of limiting the rise in upstream water level in comparison to a conventional overflow spillway. In fact, over 80% of the spillways built recently the world over for discharges in excess of 5000 m^3/s are of the gated type and for discharges in excess of 15,000 m^3/s, the gated spillway is used invariably (Lafitte, 2007). Generally, the sill of such spillways would be at a relatively low level, which means that the gates of these spillways have to operate at high heads. The following advancements in Gate Technology in the last 3 - 4 decades have made the construction of such spillways possible:

(i) Development of self-lubricating bearings, which allow for significantly higher thrust on the bearings of segment gates;
(ii) use of sealing materials such as Teflon-coated seals;
(iii) high pressure hoist cylinders;
(iv) pre-stressed anchors; and
(v) improvement in steel quality and coatings, which increase the abrasion resistance of steel linings.

The provision of such large capacity sluices at a relatively low level for handling floods offers the possibility of also using them judiciously for sediment control. Consequently, such spillways are viewed at present not merely as structures for handling floods but as those which enable integrated sediment water management. In cases where the ratio of the reservoir capacity to the annual inflow of water is less than 1.0, one has the freedom to let the highly sediment-laden flows pass through the spillway and store the relatively clear water, thereby reducing the sedimentation in the reservoir. Such a policy called DTSC (Discharge the Turbid and Store the Clear) has been used successfully by China on several of its reservoirs. The currently used practices of `Sluicing', `Flushing' and `Venting of density currents' for sediment control have all become possible as a result of the presence of relatively large-size low-level sluices in the dam. The above practices may be used for reducing the progressive loss of capacity due to sedimentation in dead and live storage zones and also to provide a favourable sediment environment near the intake (usually power intake) to minimize sediment entry into the intake.

4.5 Flushing and Sluicing of Sediment from Reservoirs

The basic principle involved in both flushing and sluicing is that it is possible and economical to entrain and erode the deposited and unconsolidated sediment or keep the incoming sediment moving on the reservoir bed by flows within the reservoir; eventually the sediment-water mixture is flushed out through the dam outlets. The sediment already in motion within the reservoir in the form of density currents can also be removed by venting of the density currents. The action when flow is released from reservoir by maintaining relatively constant water level in a reservoir, is termed as reservoir sluicing. The action when reservoir releases are made by allowing drawdown or emptying of the reservoir is termed as reservoir flushing.

Reservoir flushing and sluicing have been followed with varying degrees of effectiveness in India and in other countries including USA, China and Egypt. It may, however, be noted that a significant part of the reservoir water storage is lost in flushing of the reservoir. It may or may not be possible to fill the reservoir completely when sluicing is resorted to.

Sluicing as well as flushing have not been found very effective in reducing the problem of reservoir sedimentation unless the undersluices are provided near the original bed level of the river. However, operation of the sluice gates having depths less than 100 m or so from the water surface only is feasible. Intermediate level sluices are instead used in high dams due to lift requirements of high head gates like in Tehri reservoir. Mostly the undersluices provided at levels higher than the original bed level of river are much less effective in silt removal.

Generally speaking, no drawdown is envisaged in sluicing. Instead the filling of the reservoir during a flood is delayed or so planned that reservoir levels are low during the first floods of the season or the rising stage of a major flood. This would cause the velocities in the reservoir to be relatively high and thus cause most of the sediment to be carried to and through the sluices. Thus the sedimentation in the reservoir, is greatly reduced particularly if the sluices are located near the river bed level. On the other hand, if the sluices are located at higher levels, sluicing would still ensure riverine conditions for some distance upstream of the sluices, with a relatively steep slope. If the intake is located immediately upstream of the sluices and the sill of the intake is about 10 20 m higher than that of the sluices, sluicing would yield a favourable sediment environment near the intake and reduce sediment entry into the intake.

Flushing invariably involves reduction of reservoir level at some convenient time after it has been filled up, thereby increasing the velocities adequately enough to cause erosion of the deposited sediment and flush out the sediment-laden water through the sluices. For flushing to effectively reduce sedimentation, the sluices need to be located at the river bed level, as they generally are.

4.5.1 Case Studies

Sluicing has been successfully employed in 3024 Mm^3 Roseires reservoir on Blue Nile, Sudan, 5300 Mm^3 Old Aswan dam, Egypt (Mahmood, 1987), 3540 Mm^3 Sanmenxia reservoir and several small reservoirs on the Yellow river in China (ICOLD, 1999). These dams are provided with several low level sluices to pass the flood. Sluicing operation in the Matalia dam in India lowered the trap efficiency from 90% to 70% and this was achieved by releasing the first flood peak of the season without impounding (Govt. of India, 2005). The experience on a few other Indian reservoirs is also described here as given by Asthana (2007) and Govt. of India (2005).

Four low level sluicing outlets have been provided at Chamera II dam built on river Ravi in Himachal Pradesh. These have been operative since the commissioning of the project and are functioning satisfactorily. Low level sluices are also provided in the dam body of Nathpa Jhakri power project. During the flood season the reservoir of Nathpa-Jhakari dam is flushed during the night of weekend by emptying it. All the deposited sediment, which mostly consists of coarse sediment is flushed out from the reservoir through flushing. The power plant, however needs to be shut down during periods of high suspended sediment load in the flow. The fine sediment of the river consists mainly of quartz components having high value of hardness. Such fine sediment does not deposit even in large size settling basins and it inflicts damages on turbine blades due to the high head of 300 m used for power generation (see Fig. 4.5).

Fig. 4.5 Damage of turbine blade due to fine sediment in Nathpa-Jhakri hydro power project

In 198 MW Baira-Siul project in India, for the combined flow of 88 m^3/s of rivers Baira, Siul and Bhaledh, the desilting arrangements are provided at three locations. First of these is the Baira reservoir which provides for diurnal storage and acts as a siltation tank. The reservoir gets filled up with silt very fast upto the intake level. Subsequently the silt encroaches to above the intake level, the bed load enters into HRT and damages the turbine and other appurtenances. To reduce damages to turbines etc., the Baira reservoir is flushed through spillway and the diversion tunnel. The reservoir is emptied through spillway gates upto about intermediate level and through diversion tunnel below it when inflow to the reservoir is in excess of 100 m^3/s. After emptying, flushing or normal river flow is allowed for 24 hours period when most of the deposited sediment is flushed out. This operation is performed at least once in a year when the powerhouse is shut down. The flushing, however, causes damage to diversion tunnel lining which is generally repaired after the monsoon season.

Sluicing with controlled releases during lean season also has been successfully done to wash accumulated sediment in Kundah Palam reservoir (Tamil Nadu) through low level outlets. However, large amount of water storage is lost in this process. During any one of such operations the reservoir is completely depleted so that the deposited sediment is loosened. The deposited and loosened silt is flushed out next by releasing significantly large volume of flow over a duration of about 10 days (Stephen, 1999).

The reservoir of 137 m high Tarbela dam in Pakistan having a storage capacity of 14200 Mm^3 was not provided with provisions for sediment management. As a result the reservoir lost about 17.4% of its capacity due to siltation until 1992 (Morris and Fan, 1997). The reservoir receives about 208 M Tones of sediment load per year which consists of 59% fine sand, 34% silt and 7% clay and trap efficiency of reservoir is about 49%. The longitudinal profile of sediment deposition is shown in Fig. 4.6 (Asthana, 2007).

Sluicing with high level outlets is now proposed to be performed for flushing sediment from the reservoir of the Tarbela dam. Provision of normally submerged rock fill dyke consisting of a dam on upstream such that the deposition delta formation is restricted in areas that are more than 8 km on upstream of main dam and do not encroach up to the intakes. This provision is estimated to considerably delay the sediment deposition problem. The sediment deposition upstream of the dyke is proposed to be flushed out through high level by-pass channel of capacity 5000 m^3/s around the dam having invert level 80 m above original bed level of river and also above power intakes. The conceptual plan for by-pass channel is shown in Fig. 4.7 (Morris and Fan, 1997). Flushing of the reservoir through the proposed measures is planned to be carried out during the initial floods of the monsoon period.

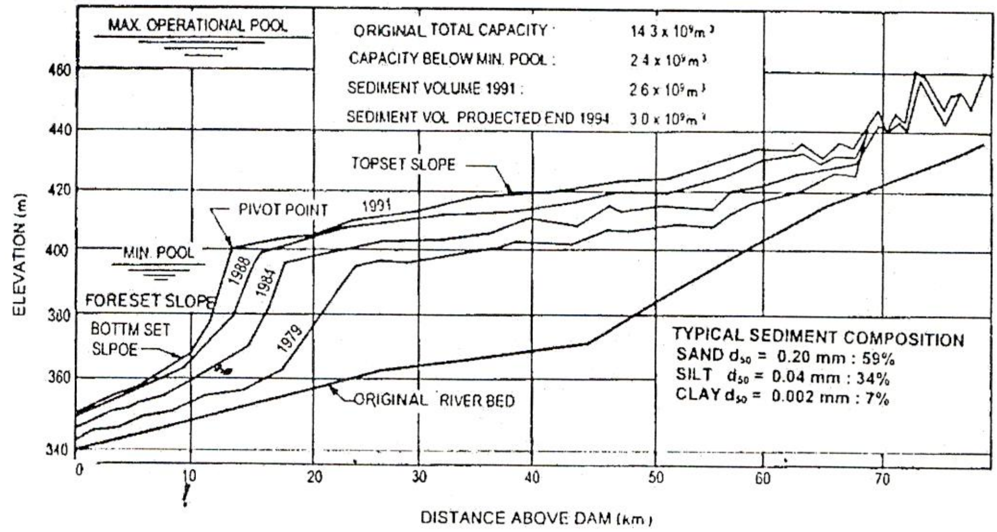


Fig. 4.6 Sediment deposition profiles in Tarbela dam, Pakistan (Morris and Fan, (1997)

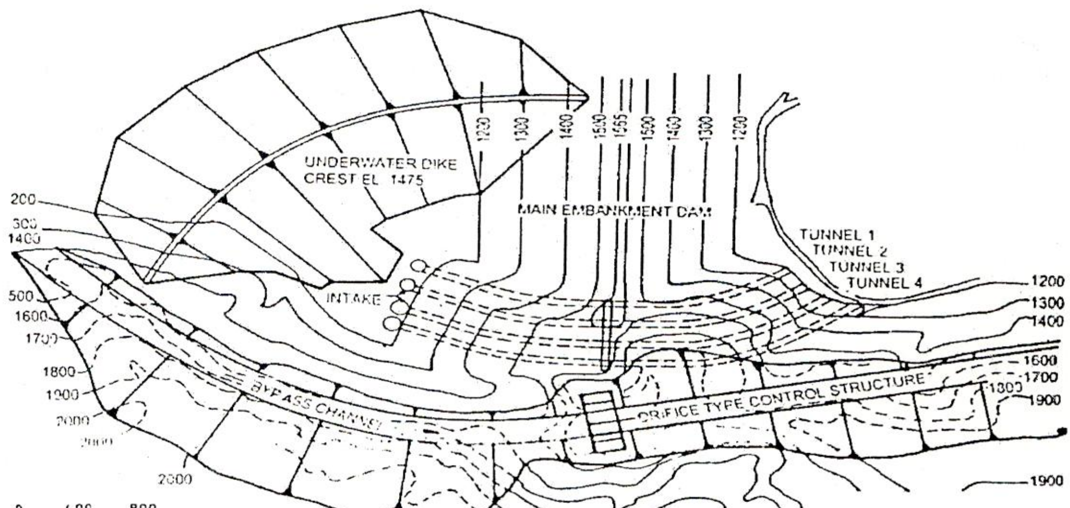


Fig. 4.7 Proposed configuration for sediment bypass arrangement for Tarbela dam, Pakistan (Morris and Fan, (1997)

It would be of interest to mention about the effect of drawdown flushing in case of the Welbedacht reservoir on the Caledon river in South Africa (ICOLD, 2007). The dam was built in 1973 and by 1991, it had lost 97 Mm^3 its original capacity of 114 Mm^3. The dam is equipped with 5 gates located about 15 m above the river bed. Two flushings during October 1991 using these gates helped in recovery of a fair amount of storage; see Figs. 4.8 and 4.9.

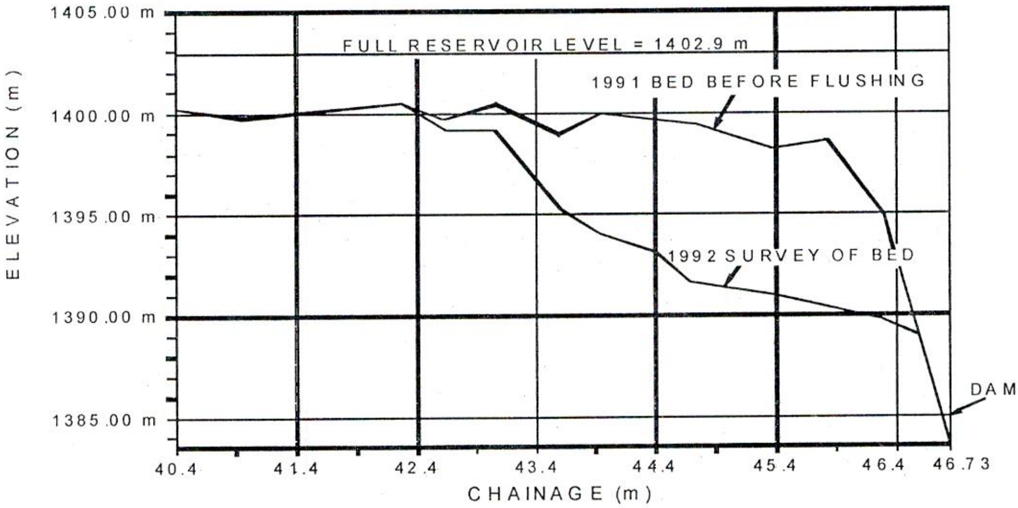


Fig. 4.8 Observed flushing channel bed profiles at Welbedacht reservoir (ICOLD, 2007)

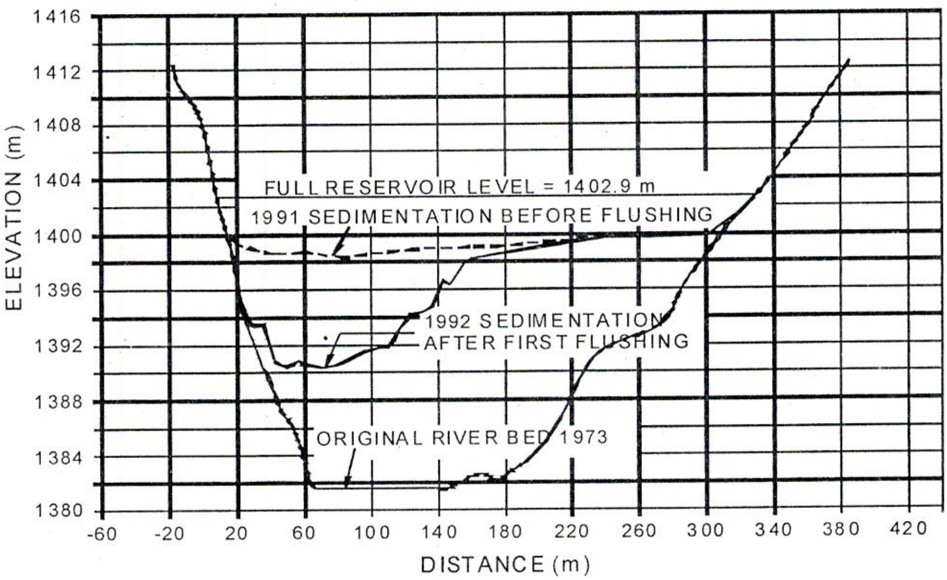


Fig. 4.9 Cross section of Welbedacht reservoir slightly upstream of the dam (ICOLD, 2007)

White (2001) has presented the state of art on reservoir flushing and summarized it as below:

- The hydrology and sedimentology of the catchments need to be fully understood in the planning of flushing facilities for new or existing reservoirs and need to provide the background for analyses of past sedimentation and flushing performance.
- Successful hydraulic flushing is more likely to be practicable in reservoirs that are hydrologically small having a storage capacity less than 30% of the mean annual inflow.
- The smaller the reservoir, the greater the chance of it being successfully flushed for reclaiming the original storage capacity.
- Flushing is vital for the preservation of long-term storage in reservoirs where the sediment deposition potential is greater than 1 to 2% of the original capacity. Even in large reservoirs with a potentially long life, consideration should be given to possible eventual decommissioning problems when deciding whether or not to flush.
- The shape of the reservoir basin can have a large impact on the practicability of effective flushing and on the residual storage capacity. Narrow steep-sided reservoirs in valleys with a steep longitudinal slope are the easiest to flush. Wide valleys, where the impoundment covers former flood plains, can be flushed less effectively, because the deposit tends to consolidate and is remote from the flushing channel.
- For effective empty flushing with full drawdown, the low-level outlets must be both low enough and of sufficient capacity to allow the drawdown to be controlled during the time of year when flushing is undertaken. Proportionately large outlets are required for flood season flushing.
- Operational considerations, such as water and power demands can inhibit the ability to flush successfully but they must not be allowed to prejudice the long-term preservation of an important resource.
- Full drawdown and empty flushing have been found to be much more effective than partial drawdown.
- Fluctuations in water level and discharge during flushing are also causes of bank slumping and increasing the rate of sediment discharge.
- The deployment of lateral and longitudinal diversion channels has been successful in promoting flushing in reservoirs that are hydrologically large or that contain significant proportions of deposition in areas remote from the main flushing channel.
- Downstream impact can act as a constraint in the planning and operation of flushing. In some cases flushing may be ruled out, whereas sluicing, which approximately preserves the seasonal distribution of sediment load, may be a practicable alternative.
- The degree of success in flushing should be judged by whether it makes a worthwhile difference to the beneficial uses of the reservoir, rather than simply by whether it meets other objectives, such as a long-term balance between inflows and outflows, or the retention of a certain percentage of the original storage volume.

Take 4.2 gives details of low-level sluices for flushing and sluicing on several run-of-the-river hydroelectric projects in India and Bhutan. Generally speaking flushing has been more effective in those cases in which the sluices are close to the river bed. Sluicing has also been effective on several storage projects in China, e.g. Sanmenxia, Xiaolangdi and Three Gorges. Figure 4.10 shows the outflow from a high level and a low-level sluice of the Xiaolangdi reservoir. There is obviously no drawdown since the high-level sluice is discharging. The highly sediment-laden water coming out through the low level sluice is an indication of the effectiveness of sluicing even at a high reservoir level in this case.

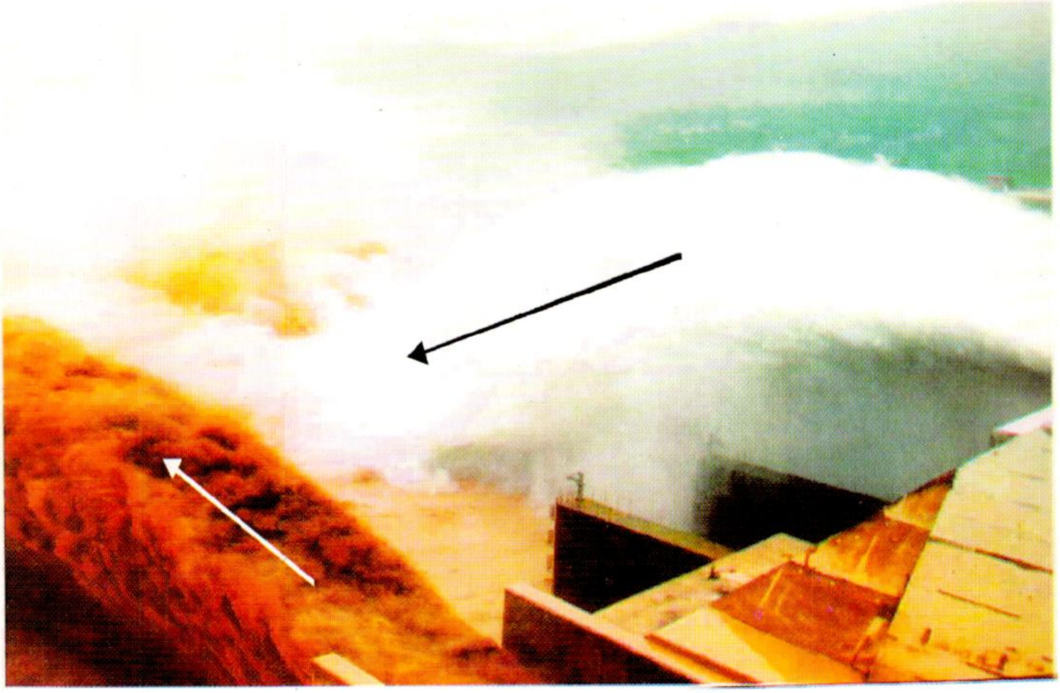


Fig. 4.10 High-level and low level sluices in operation in Xiaolangdi dam, China

Table 4.2 Details of Low-Level Sluices for Sediment Control in some Run-of-the River Hydro-projects

Sl. No.	Dam/Reservoir, River (Country)	No. and size of Sluices	Sill level of Sluices	FRL	Sill level of power intake	River Bed level
1.	Chamera-I Ravi (India)	8 no, 10.0m×12.8 m 4 no; 4.0m×5.5 m	730.0 m, 670.0	760.0 m	733.0 m	644.0 m
2.	Nathpa Jhakri Sutlej (India)	5no., 7.5m×8.5m	1458.0m	1495.5m	1463.5 m	1451. m
3.	Kurichu Kurichu (Bhutan)	5 no., 10.5m×14.0m	506.0 m	531. m	520.4 m	481.3 m
4.	Teesta Stage-V Teesta (India)	5 no., 12.0m×9.0m	540.0 m	579.0 m	554.0 m	540.2 m
5.	Subansiri Lower Subansiri (India)	9 no., 11.5m×14.7m	150.0 m	205.0 m	160.0 m	94.0 m
6.	Chamera –III Ravi (India)	3 no., 12.5m×16.5 m	1360.0 m	1397.0 m	1369.0 m	1344.0 m
7.	Myntdu Myntdu (India)	7 no., 8.0m×12.0 m	587.5 m	618.0 m	598.81 m	564.0 m
8.	Tala Wangchu (Bhutan)	5 no., 6.5m×13.15 m	1320.0 m	1363.0 m	1335.0 m	1291.0 m

4.5.2 Volume of flushed sediment

On the basis of observations for discharge of fine sand (d_{50} = 0.06 to 0.09 mm) from Sanmenxia dam, an empirical relationship was proposed Fan and Jiang (1980) as

$$Q_s = 3.5\times10^{-3}\, Q^{1.2}\, (S\times10^{4})^{1.8} \tag{4.1}$$

where Q_s is sediment discharge being flushed out (Tonnes/s), Q is water discharge (m^3/s) and S is water surface slope. Similarly, based on field data on emptying of the reservoirs by flushing in China, Xia (1983) proposed an empirical relation as

$$Q_s = \frac{EQ^{1.6}S^{1.2}}{B^{0.6}} \tag{4.2}$$

where B the channel width which may be predicted by the relation $B = \dfrac{1.5Q^{0.5}}{S^{0.2}}$ in which E is erodibility coefficient, the value of which is dependent on sediment size and Q is expressed in m^3/s. Atkinson (1996) tested the relationships listed above for their accuracy by using data from small reservoirs in India, USA and Russia and proposed a modified relation for Q_s as

$$Q_s = \frac{E^{1/3} Q^{1.6} S^{1.2}}{B^{0.6}} \tag{4.3}$$

4.5.3 Venting out the turbidity currents

Density currents, also termed as turbidity currents, are developed in reservoirs when suspended sediment laden inflows enter into reservoir having relatively clear water; the density difference between the incoming flow and the reservoir water drives the flow. Only fine sediment is transported by the density currents.

Turbidity currents can travel long distances in reservoirs under favorable conditions. In lake Mead the turbidity currents are reported to travel by about 129 km to reach upto the face of the dam (ICOLD, 1989). Several reservoirs in China like Guanting reservoir on the Yongding river, Sanmenxia and Luijiaxia reservoirs on the Yellow river have been noticed to carry density currents. The following conditions have been identified as being favorable for the development of density currents (ICOLD, 1999).

- River bed slope should be steep
- Inflow to the reservoir should transport suspended load with high concentration
- Reservoir should have gorge type shape.
- Reservoir depth should be large and flow velocity in it be small
- Large difference should exist between density of the inflow and reservoir water.

Experiments carried out in China have indicated that density currents can be vented out through outlets located below a certain height from the original bed level. The following expression can be used for determination of such a height h_L (Batuca and Jordaan, 2000).

$$h_L^{\cdot} = 0.154\left(\frac{\rho Q_o^2}{\Delta\rho g}\right)^{1/5} + 0.5\frac{\rho_{susp} q^2}{\Delta\rho g h^2} \tag{4.4}$$

where h_L = maximum climbing height (m), Q_o = outlet capacity (m^3/s), q = flow rate of density current per unit width (m^3/s-m), h = height of density current (m), ρ_{sump} density of density current (kg/m^3) and $\Delta\rho = \rho_{inflow} - \rho_{reservoir}$. The expressions for working out depositions within the reservoir due to density currents are described in Section2.

Observations on reservoirs in China and USA have revealed that venting efficiency of density currents (ratio between out flowing and incoming sediment load in percent) varied from 57 to 84%. There is very little information about occurrence or otherwise of density currents in Indian reservoirs. The theory and the modelling of density currents are discussed in detail by ICOLD (2007).

4.6 Rehabilitation of Reservoirs

Reservoir Rehabilitation measures are adopted for clearing the deposited sediments as a last resort with the objective of partially or fully restoring the reservoir storage capacity lost due to sedimentation.

Hydraulic and Mechanical methods are used for reservoir rehabilitation. Hydraulic method of siphoning and mechanical methods comprising excavation and dredging are in use (Asthana, 2007). Sometimes a combination of the two methods is also used to improve the efficiency.

4.6.1 Hydraulic Method - Siphoning

Sediment siphoning is the process of removing deposited sediment from reservoirs by accelerated pressurized flow in a pipe crossing the dam using siphon suction dredger also known as hydro aspirator (Asthana, 2007). For siphoning the sediments the delivery pipe-line is sometimes taken to the downstream by crossing it over the dam crest. However, mostly the pipeline passes through the bottom outlet existing in the dam body. When the outlet pipe crosses the dam crest, its functioning is limited to about 8 m to 10 m (atmospheric pressure) difference between the reservoir water level and the top of the pipe. A vacuum pump is required to start syphonic action in such cases; however, a vacuum pump is not required when the outlet pipe passes through the dam outlet, since the head difference between the water level in the reservoir and that downstream of the dam provides the head causing suction and siphoning. A siphon suction dredger consists of the following three main components (Fig. 4.11; Batuca and Jordaan, 2000).

- Motorized floating barge capable of quick movement within the reservoir, which should also have arrangement to support the suction head at varying depths.
- A flexible pipeline of required length with suction head at the upstream end and a control valve (if required) at the downstream.
- A number of pantoons to support the pipeline either at the water surface or at certain depth below the water surface.

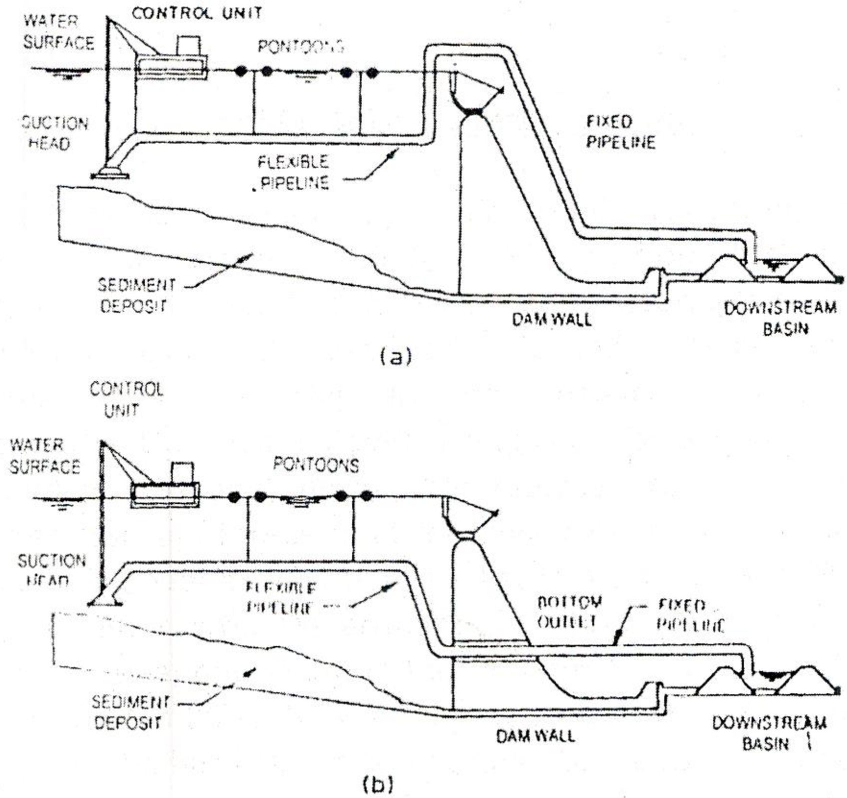


Fig. 4.11 Arrangements for sediment siphoning (a): siphoning through the dam top (b) siphoning though dam outlets (Batuca and Jordaan, 2000)

The deposited sediment is sucked by placing the suction head on the bed surface of the reservoir due to hydraulic pressure and transported through out pipelines. Some variants of siphoning have been developed and these are described below.

The sediment evacuation pipeline system (SEPS) is a form of the sediment siphoning, which consists of a pipeline laid on the reservoir bed sediment deposits. At the other end the pipe takes out through the low-level outlet in the dam and discharges water-sediment mixture into the downstream. The system works under the difference in head between the reservoir surface and tail water levels. It is similar to a siphon but needs no priming. The SEPS process was used in Djidiouia reservoir in Algeria (Fan, 1983). It has been successfully used on a small project on White Tail Creek in Western Nebraska USA and several small dams in Italy (Hotchkiss, 1994).

The Norwegian Institute of Technology developed SEPS with slots on the pipe bottom pipe. This system was tested for sediment evacuation in Jhimruk reservoir, Nepal in 1994.

The SEPS with hydro aspirator has also been used successfully for sediment siphoning in Tianjiawan reservoir and Youhe reservoir in Shanxi, China. It is used on the intake of a 24 m high arch gravity dam (Rioumajou dam) in France. This system has been also used in Stefanesti, Prundu, Clucreasa reservoirs in Romania and Rioumajou dam, France (Batuca, and Jordaan, 2000).

4.6.2 Mechanical measures

Mechanical measures like excavation or dredging of deposited sediments are costly and time-consuming. However, such methods are used only when other measures are not economical or effective.

(i) *Excavation*

Emptying of the reservoir is required for excavation and removing the sediment manually or through excavation by using conventional earth moving equipment such as shovel, dragline, clamshell along with hauling units. Excavation of consolidated clay and silt is rather difficult than excavation of sand and gravel. Therefore, generally, coarse sediment deposits which occur on upstream reach of reservoir can be removed mechanically. However, manual and mechanical excavation is frequently used to help flushing operation when deposits are dozed to scour in the deep pool near the sluices in the dam. Flushing and excavation operation in Kundah Palam reservoir in Tamil Nadu has been used to remove the loosened deposited sediment (Stephen, 1999). Manual excavation is, however widely practised in small reservoirs in China, India and Indonesia. Mechanical excavation was performed in 1993-96 for rehabilitation of 11 Mm^3 Logs Well Dam, USA by excavating 2.4 Mm^3 deposited sediment in it (Asthana, 2007).

(ii) *Dredging.*

The principle involved in dredging of sediments deposited in reservoirs is the same as that that of river waterway dredging. Dredging is defined as the process of moving deposited sediment under water within the bottom of the water body like reservoir from one place to another. The dredger used for dredging is always kept afloat on water and it excavates sediment from the bottom of the reservoir (Asthana, 2007). The process of dredging can be performed mechanically or hydraulically. Asthana (2007) has presented a detailed description of different types of dredgers.

Dredging operations have been carried out on some reservoirs having relatively small size. As per Okada and Saba, (1982) the disposal of the dredged material at Sakuma reservoir, Japan was done through a 16 km long pipeline with three booster pumping stations. Similarly, Breusers et al., (1982) reported that dredged material from reservoirs was transported through 18 km long pipeline with the help of 10 booster pumps in the Netherlands. In India, dredging has been adopted to maintain live storage of the balancing reservoir of the Beas-Sutlej link project. However concerns have been expressed on the environmental effects of the disposal of dredged sediment in the context of the Beas-Sutlej link project (Asthana, 2007). Hydraulic dredging entails significant use of water from reservoir storage for pumping out the water-sediment slurry.

4.7 Sediment Extraction

The discussion in Section 4.0 so far has been concerned with controlling deposition of sediment in reservoirs. Such control is necessary to reduce the rate of sedimentation in the reservoir and also to provide a favourable sediment environment near the intake in case of hydropower projects. The measures described in the earlier part of Section 4.0 may not always ensure that coarse sediment does not enter the intake. It is also possible that the concentration of sediment entering the intake is high.

It is generally believed that sediment coarser than 0.20 mm in size is harmful for turbine blades and will thus have to be eliminated from power channels. Also if the incoming sediment load is in excess of the carrying capacity of the canal, the excess load needs to be removed to maintain the stability of the channel. Such extraction devices are located a short distance downstream of the entrance of the intake structure. Considering the general situation in which there is a significant fraction of sediment in suspension that needs to be extracted, settling basins and vortex chamber extractors stand out as feasible methods of extraction which can be used in such cases. The methods of design of such structures are briefly discussed.

4.7.1 Settling basins

Settling basins operate on the principle of forcing sediment to deposit through a significant reduction in velocity. The reduction in velocity is achieved by an increase in width and an increase in depth (Fig. 4.12).

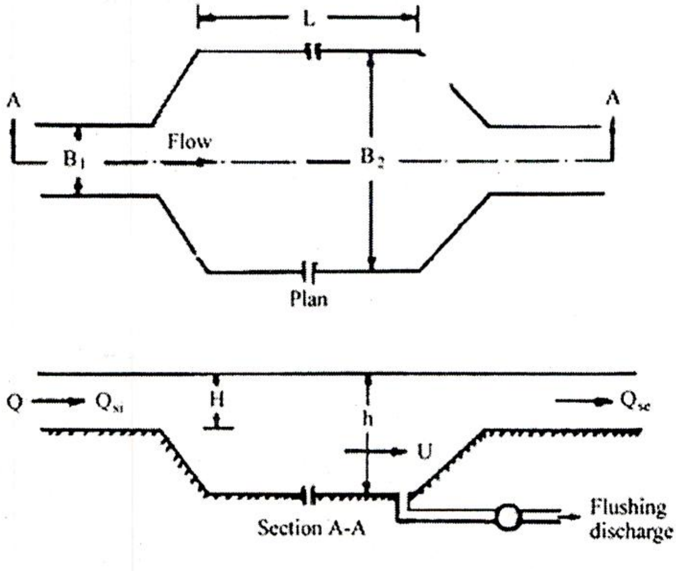


Fig. 4.12 Definition sketch of a settling basin

Settling basins may have continual flushing in which case the incoming discharge has to exceed the design discharge by the discharge used for flushing - for removal of deposited sediment or may only rely on intermittent mechanical or manual removal of deposited sediment. Ever since the early work of Dobbins (1944), several empirical and semi-empirical relations for the efficiency of sediment removal of settling basins have been obtained. Some of these are those due to Sumer (1977), Schrimpf (1991) and Atkinson (1992).

Dongre (2002) performed laboratory experiments on the efficiency of settling basins and also checked the accuracy of the available relations for efficiency. Finding that none of the available relations was satisfactory over a wide range of variables, he derived the following empirical relation for efficiency based on analysis of all the available data:

$$\eta = 102.5\left(1-\exp\left(-0.3\frac{A_b}{A_a}\right)\right)\left(1-\exp\left(-0.1\frac{L_s}{h_s}\right)\right)\left(1-\exp\left(-0.42\frac{\omega}{u_*}\right)\right) \qquad (4.5)$$

Equation (4.5) is applicable for settling basins without flushing. Here η is the efficiency of the basins expressed in percentage, A_b is the area of cross section the settling basin, A_a is the area of cross section of the approach channel and u_* is the shear velocity in the settling basin L_s is the length of the settling basin whereas h_s is the flow depth in the settling basin. Fig. 4.13 shows that Eq. (4.5) is able to estimate η values with a maximum error of about $\pm 25\%$.

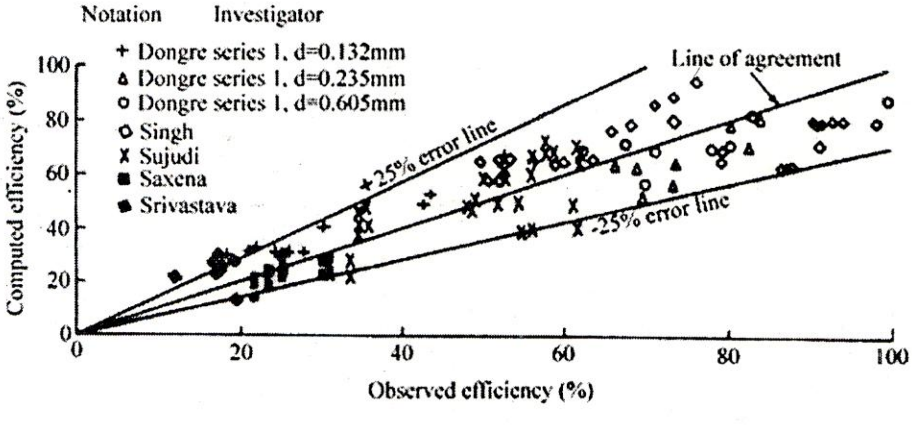


Fig. 4.13 Comparison of observed efficiency with computed efficiency using Eq. (4.5)

The effect of continual flushing on the efficiency of the basin was taken into account by Ranga Raju et al. (1999), who proposed

$$\frac{\eta_f}{\eta} = 1 - 0.12 Q_f^{-0.105} \left(\frac{\omega}{u_*} \right)^{0.312} \tag{4.6}$$

Here η_f is the efficiency in the presence of flushing, η is the efficiency in the absence of flushing and Q_f is the flushing discharge expressed as a percentage of discharge entering the basin. Fig. 4.14 shows that the error in estimation of efficiency from Eq. (4.6) is generally less than $\pm 8\%$.

A variation of the settling basin shown in Fig.4.12 has been used on the Yamuna hydroelectric Scheme II in India. A discharge of 235 m^3/s is diverted through a 7.0 m diameter and 6.3 km long tunnel to feed the power house. A settling basin with hoppers is constructed just upstream of the tunnel; see Fig. 4.15. The coarser material settles in the first hopper and finer material in the hoppers downstreacm and the sediment settled in the hoppers is flushed through a 0.80 m×2.0 m conduit. The flushing discharge is 35 m^3/s, i.e. 32% of the diverted flow. The settling basin has an efficiency of 90%.

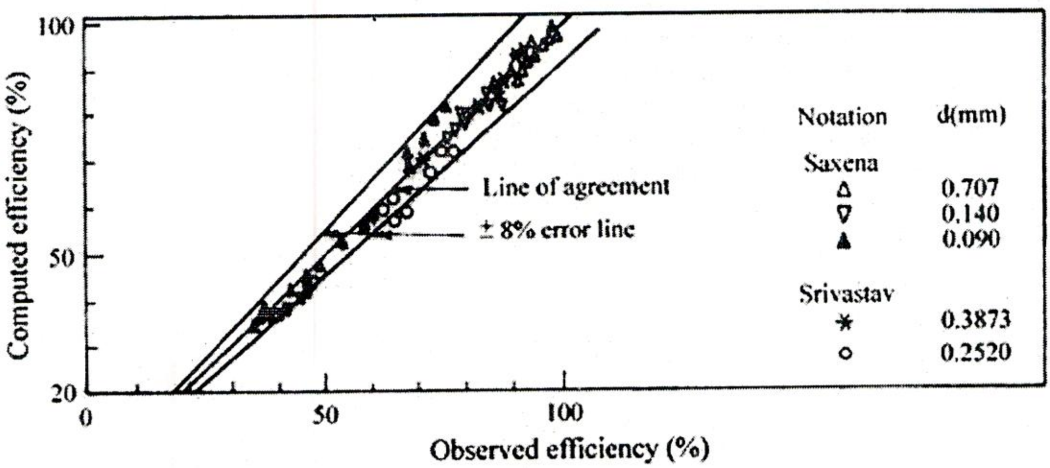


Fig. 4.14 Comparison of observed efficiency with computed efficiency using Eq. (4.6) (basin with flushing)

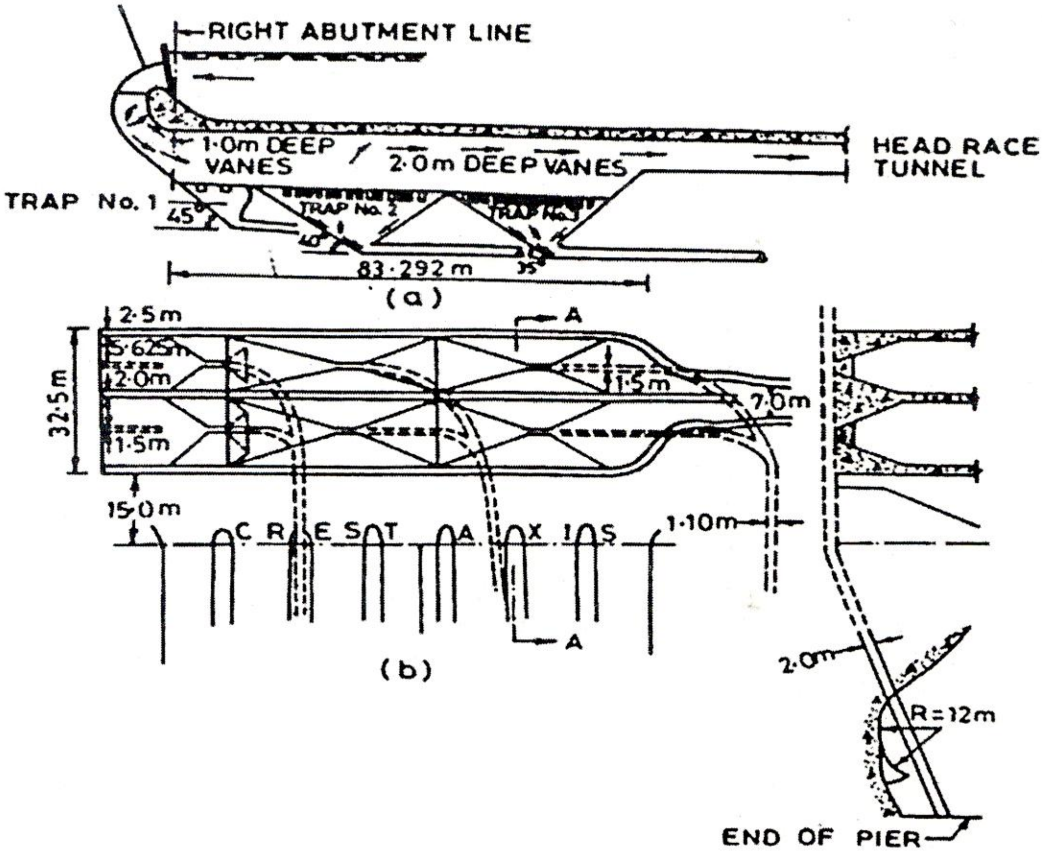


Fig. 4.15 Settling basins with hoppers used on the river Yamuna (a) longitudinal section (b) plan and (c) cross section (Garde and Ranga Raju, 2006)

4.6.2 Vortex chamber type extractor

This type of extractor makes use of vortex flow in a chamber for sediment removal. A high velocity flow is introduced tangentially into a cylindrical chamber having an orifice at the center of its bottom, which removes the highly sediment concentrated flows. This, along with tangential entry of flow causes combined (Rankine type) vortex conditions with free vortex forming near the orifice and forced vortex conditions forming in the outer region towards the periphery. Vortex flows cause a sediment concentration gradient across the vortex and a diffusive flux proportional but opposite to the centrifugal flux (Julien, 1986). The secondary flow resulting from this phenomenon causes the fluid layers near the basin floor to move towards the outlet orifice at the center.

The sediment particles present in the flow move along a helicoidal path towards the orifice, thereby experiencing a long settling length compared to the chamber dimensions. The sediment reaching the center can be flushed out through the orifice into an outlet channel or pipe.

The vortex chamber type of extractor has been investigated by Cecen and Bayazit (1975), Curi et al. (1979), Mashauri (1986), Zhou et al. (1989), Paul et al. (1991) and Athar et al. (2002). As compared to the settling basins and tunnel type sediment extractors, these have the advantage of smaller dimensions and low flushing discharge for obtaining a certain efficiency of sediment removal (Mashauri, 1986, Athar et al., 2002). Recently Pandit et al. (2008) proposed use of hydrocyclone exclusion of fine sediment from inflows. Hydrocyclones are structures having similar geometry as the vortex chamber extractors. However, use of these extractors is limited to small size power projects as a circular chamber having diameter about five times that of the inflow channel width is needed for efficient extraction.

According to Mittal (2009) the initial cost of providing desilting basins is high in case of small and medium size hydro projects. Alternative measures however could be: (i) Using turbine runner blades having higher abrasion resistant coatings and (ii) Provide provisions for frequent replacement of turbine runner blades.

The savings of cost thus achieved should however be weighed against the recurrent revenue loss due to frequent closures of the power house which shall be necessitated for repair and replacement of the turbine runner blades.

5.0 CONCLUSIONS

It is imperative that the capacity of existing reservoirs built on alluvial rivers is not allowed to go down significantly because of economic and environmental considerations. Reservoirs of the future need to be planned to ensure their sustainability from the point of view of sedimentation. Mathematical models offer a scientific tool for analyzing the process of sedimentation in a reservoir. Operations like sluicing and flushing using large low-level sluices greatly reduce sedimentation in reservoirs. Such sluices are ideally suited for integrated sediment and water management and enable judicious polices like Discharge the Turbid and Store the clear (DTSC) to be adopted.

Sediment yield models help in identifying priority areas for catchment area treatment for controlling sediment inflow to reservoirs. Many times measures for controlling sedimentation may not satisfy the requirements (from the point of view of sediment) of the hydropower plant at the reservoir. Settling basins or vortex chamber extractors may then need to be used to additionally control the quality and quantity of sediment entering the turbines.

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India's Participation in IHP-VII Program

Theme	Selected Focal Areas
Theme I: Global Change, Watersheds and Aquifers	1. Water resources management under drought situation 2. Assessment of water resources under climate change
Theme II: Ecohydrology and Environmental Sustainability	3. Real time flood forecasting 4. Flood inundation zoning for different return periods
Theme III: Water Quality, Human Health and Food Security	5. International conference on water, environment, energy and society (WEES)

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