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Design of Hydroelectric Projects for Sediment Management

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ABSTRACT: The design of the reservoir upstream of the dam and of the canal requires consideration of the sediment load carried by the river in case the river is sediment-laden. The hydraulics of lined canals is described from the point of view of limiting transport capacity and changes in frictional resistance. The processes of sediment yield, reservoir siltation are also discussed. Methods of design of sediment extraction devices like settling basins and vortex chambers are presented.

INTRODUCTION

Sediment transport and its accumulation can have profound effects on the performance of hydropower projects and facilities. Blades of turbines in hydropower projects and other appurtenant structures of dams frequently get damaged due to abrasion by sediments. There are many dams and reservoirs around the world where long before the predicted project life the reservoir sedimentation has reached such a stage that adequate power generation is no longer possible. Remedial measures which would eventually restore at least partially their initial power generation is worth trying. As in most cases the maximum percentage of sediment is transported during the onset of flood flows. Detailed information regarding the major flood hydrographs and the estimate of corresponding total sediment load deposited in the reservoir should therefore be gathered for precise sediment management. There is no better tool other than the reliable mathematical and physical model simulations of the actual process of sediment transport, deposition and removal as well as its impact on long-term behavior of the dam appurtenances which can be studied during flood flows and also during low flows. Considerable development has taken place in recent past on this topic which is of great practical importance.

Alluvial, gravel and boulder bed rivers pose several challenging problems in the design of runoff the river and storage type hydroelectric projects built on them and of conduits or canals taking off from them on account of the complex role played by the sediment load they carry. Construction of a dam or a weir and withdrawal of water from the river invariably disturbs the equilibrium of the river leading to aggradation and degradation in different reaches of the river. As such, design of reservoirs and canals in the case of alluvial rivers requires a clear understanding of the influence of the sediment load carried by them and incorporating the sediment load as one of the parameters in design. Several aspects of practical importance in such designs are addressed in this paper. The contents are influenced to a significant extent by the Indian practice in handling these problems.

RESERVOIR SEDIMENTATION

Run-of-river schemes involving the construction of a diversion structure like a weir or a barrage of relatively small height are implemented when the water demand is less than the minimum available river flow and also a required minimum flow can be assured in the river downstream of the point of diversion. It is generally believed that such schemes cause fewer disturbances to river regime than those that involve the construction of high dams and large capacity reservoirs. Large capacity reservoirs are, however, required in case of non-perennial streams whose discharge for several weeks or months in a year is inadequate to meet the demand. While it is true that aggradation upstream of a high dam and degradation downstream of it are much more than in case of small diversion structures, it should also be recognized that some of the benefits of a large reservoir cannot be obtained from even a series of run-of-river schemes. It is, therefore, necessary that the morphological changes caused by large reservoirs are properly analyzed and accounted for in design to make them acceptable. That would go a long way in countering the opposition in recent years to the construction of large capacity reservoirs Ranga Raju and Kothyari, 2005).

One of the important practical problems related to the performance of reservoirs is the estimation of progressive reduction in storage capacity due to sedimentation. In its simplest form, the method involves the estimation of the annual sediment yield from the catchment, determination of the fraction of this which would deposit in the reservoir based on a knowledge of its trap efficiency and computation of the deposition profile following a method like the Empirical Area Reduction method (Borland & Miller, 1958) from which the reduction in storage capacity at various elevations can be worked out. The relationship given by Brune (1953) for trap efficiency (T_e) as a function of the ratio of storage capacity (V) to annual water inflow volume (I) should be deemed to be a satisfactory tool for the determination of trap efficiency (Figure 1). Several methods of estimation of sediment yield are available (Garde and Kothyari, 1987; Kothyari, *et al.* 2002, Walling, 1994); use of any of these methods along with the relationship for trap efficiency and the application of the Empirical Area Reduction method enables determination of sedimentation rates for purposes of preliminary design. Methods for prediction of sediment yield from catchments are discussed in detail in the next section.

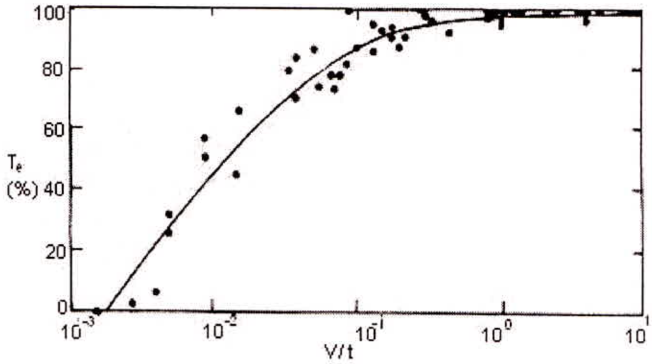

Fig. 1: Trap Efficiency of Reservoirs (Brune, 1953)

By solving numerically the governing equations, one can carry out a more detailed analysis of the process of sedimentation in reservoirs as well as of degradation downstream of dams. The fully coupled model applicable to one-dimensional analysis may be described by the following set of equations (Krishnappan and Snider, 1977):

Flow continuity equation,

$$\frac{\partial Q}{\partial x} + P\frac{\partial z}{\partial t} + B\frac{\partial h}{\partial t} = 0 \qquad \ldots (1)$$

Flow momentum equation,

$$\frac{\partial Q}{\partial t} + \frac{2Q}{A}\frac{\partial Q}{\partial x} - B\frac{Q^2}{A^2}\frac{\partial h}{\partial x} - \frac{Q^2}{A^2}\frac{\partial A}{\partial x}\bigg|_{h=const.} + gA\frac{\partial h}{\partial x} + gA\frac{\partial z}{\partial x} + gAS_f = 0 \quad \ldots (2)$$

and sediment continuity equation,

$$\frac{\partial Q_b}{\partial x} + \frac{\partial Q_s}{\partial x} + P(1-\lambda)\frac{\partial z}{\partial t} + BC_s\frac{\partial h}{\partial t} + A\frac{\partial C_s}{\partial t} = 0 \quad \ldots (3)$$

where z = bed elevation, B = water surface width, x = distance along the flow direction, t = time, h = depth of flow, S_f = slope of energy grade line, Q_b = volumetric bed load discharge, Q_s = volumetric suspended load discharge, C_s = volumetric concentration of suspended load, λ = porosity of bed material and g = gravitational acceleration.

The terms S_f, Q_b, Q_s and C_s are required to be determined for obtaining the solution of the above system of equations. Auxiliary equations are used for the evaluation of the above terms; these equations are the resistance equation and the equations for the transport of bed load and suspended load. Depending on the level of sophistication aimed at, information may be required only on the total amounts of material carried as bed load and suspended load or on the transport rates of different size fractions of the bed material in both these modes of transport.

A large number of resistance and transport equations suitable for use in Eqns. (2) and (3) are discussed by Garde and Ranga Raju (2000). Some of the more commonly used models for the solution of Eqns. (1) to (3) to compute transient reservoir sedimentation profiles are those due to Lyn (1987), HR Wallingford (1996) and Singh *et al.* (2004). A discussion on these models is outside the scope of this paper.

MODELLING AND PREDICTION OF SEDIMENT YIELD

The existing sediment yield models vary greatly in complexity, from simple regression relationships, linking spatial variation of annual sediment yield to climate and physiographic variables, to simulation models. The simulation models provide a physically based representation of the process occurring in small segments of the model and routing the response of these segments to the outlet. Because of the close dependence of sediment yield process on surface runoff, the simulation models or sediment yield are integrated with models capable of simulating the rainfall-runoff response of a catchment e.g. CREAMS model and CSU Model for water and sediment routing (Kothyari *et al.* 2002). Thus the calibration of simulation *model* needs very extensive data. Also considerable improvement will have to be made in them to include the effect of spatial variation of vegetation, earthquakes etc. on erosion rates. Hence, for the yearly sediment load computation prediction equations are preferred.

The regression equations which relate the sediment yield to the catchment and hydrometerological parameters are mostly used for prediction of sediment yield from ungauged catchments. Some of the sediment yield equations developed using data from Indian catchments are discussed below:

On the basis of data from reservoirs that were then available, Khosla (Garde and Ranga Raju, 2000) obtained the equation,

Vs = 0.0032 A0.72 ... (4)

in which Vs is annual sediment yield in Mm3 and A is catchment area in Km^2. Dhruv Narain and Ram Babu (1983) used data from 17 major reservoirs in India and obtained the relation for annual sedimentation rate as,

T = 5.5 + 11.1 Q ... (5)

in which Q is the annual runoff In Mham and T is the erosion rate in m tons per year. This equation was further refined as,

T = 5.3 + 12.7 Q W ... (6)

Here W is defined as W = T /A, A being catchment area in M ha. Average value of W was found to be 1.25 M Tons/M ha. Also using data from 18 river basins, the following relationships were obtained,

T = 0.014 A0.84 P1.37 ... (7)

T = 14.25 Q0.84 ... (8)

T = 0.000000342 A 0.84 (EI30)1.65 ... (9)

in which P is average annual rainfall in cm, A is catchment area in ha, and EI30 is the product of average annual value of the sum of maximum 30 minute rainfall intensity in cm/hr and kinetic energy value E given by E = 210 + 89 log10 I30. Here E is in tons per ha m. Ram Babu *et al.* (1978) prepared Iso-erosion map of India in which EI30 contours were plotted. Since T is proportional to EI30, these contours are known as Iso-erosion contours.

A more rigorous analysis of sediment yield from Indian catchments has been carried out by Garde and Kothyari (1987). Using data from 50 small and large catchments in India they have developed the following relationship for sediment yield erosion rate Y in cm,

$$Y = 0.02 P^{0.06} F_e^{1.70} S^{0.05} D_d^{0.10} \left(P_{\max} / P\right)^{0.09} \quad \ldots (10)$$

in which S is the land slope, Dd is the drainage density in Km^{-1}, P is the mean annual rainfall in cm, Pmax is the average maximum monthly rainfall in cm and Fe is the erosion factor which is related to land use as,

$$F_e = \frac{1}{A}(0.20 A_F + 0.40 A_{UF} + 0.60 A_A + .0.80 A_g + A_w) \quad \ldots (11)$$

Where AF = protected forest area, AUF = unclassed forest area, AA = arable area, Ag = scrub and grass area, Aw = waste area and A = catchment area. Garde and Kothyari (1987) compiled the data regarding the variables on the right hand side of Eqn. (10) for all major rivers and their tributaries within India. Using data from 154 catchments they produced an Iso-erosion rate map for the India.

Estimation of Annual Sediment Yield

Garde and Kothyari (1987) derived the following equation for prediction of annual sediment yield,

$$Y_a = (0.02 F_e^{1.7} S^{0.25} D_d^{0.10} (P_{MAX} / P)^{0.19}) P_a^m \quad \ldots (12)$$

Here Ya is the annual sediment yield in cm and Pa is the annual rainfall in cm, other-notations are same as for Eqn. (10). Equation (12) is based on the assumption that the S, Dd, and (Pmax/P) do not change from year to year and yearly variation in Fe is also negligible. The value of exponent m depends on how rainfall varies from one year to other. This is quantified by the coefficient of variation of annual rainfall CV. Studies have shown that m varies from 0.6 to 0.607 as CV changed from 0.10 to 0.70. For future year wise prediction of sediment yield, one must generate annual rainfall aeries for known P and Cv and then compute sediment yield using Eqn. (12) and known m value (Garde and Kothyari, 1987).

HYDRAULIC DESIGN OF POWER CHANNELS

Power channels are invariably designed and built as lined canals. The principle of design of a lined canal is to maintain a velocity at which the fine sediment in suspension entering the canal will not settle to the boundary and yet the velocity is smaller than that which may damage the lining. The two aspects of design that are important are:

1. Sediment carrying capacity of lined canals.
2. Resistance characteristics of lined canals carrying sediment—laden flow.

Several investigations have been carried out on both these aspects during the last few decades. The salient features of some of these studies are presented below.

Sediment Carrying Capacity

Depending on the flow, fluid, sediment and channel characteristics, there exists an upper limit for sustenance of fine sediments in suspension. If the incoming sediment concentration exceeds this limiting value, sediment will start depositing on the bed.

Starting with the analytical work of Bagnold (1966) on the subject several studies have been carried out for finding the limiting sediment concentration of lined canals. Some of these are the ones due to Itakura and Kishi (1980), Arora *et al.* (1984), Celik and Rodi (1991) and Nalluri and Spaliviero (1998). An excellent review of these methods has been carried out by Khullar (2002). Khullar also performed experiments in a laboratory channel using fine sand of 0.064 mm size as the suspended sediment. Examination of all the methods using his data as well as those of earlier investigators led him to conclude that the methods of Arora *et al.* (1984) is superior to the others.

Arora et al. Method

Arora *et al.* (1984) performed extensive experiments on the carrying capacity of lined canals of various shapes using sediment of different sizes and of relative densities. Analysis of these data as well as those from other investigators has led to a criterion for deposition of fine sediments; see Figure 2. Here C_s denotes the average concentration of sediment in ppm by volume, $q = Q/B$, f is Darcy-Weisbach resistance coefficient of the bed, h_o is the central depth, γ is the kinematic viscosity of the fluid, ω is the fall velocity of the sediment of size d and $S_c = \dfrac{S}{\Delta\gamma_s/\gamma_f}$. S is the bed slope, $\Delta\gamma_s$ is the difference in specific weights of the sediment and fluid, ρs being the specific weight of the fluid and γ_s the specific weight of the sediment. The curve drawn on Figure 2 corresponds to the condition of incipient deposition and demarcates the 'deposition' regime from the 'non-deposition' regime. In case the designed channel section is found (from Figure 2) to be incapable of transporting the expected load without deposition, a steeper slope—which indicates no deposition on Figure 2—needs to be provided.

If, for practical reasons, such steepening is not possible, it is necessary to reduce the sediment load entering the canal to a value that can be safely carried without deposition by the available slope. The sediment extraction devices that can be used for this purpose are discussed later. Interestingly, Khullar (2002) found that Figure 2 can be used also for the determination of the limiting concentration of wash load carried by alluvial channels with relatively coarse bed material.

Resistance Characteristics

The effect of presence of sediment in suspension on the resistance to flow is incompletely understood at present. According to one school of thought, turbulence is damped by sediment in suspension and thus the resistance decreases. Several investigators, whose experimental results lend support to the hypothesis, support this theory. Some of these investigators are: Vanoni (1946), Vanoni and Nomicos (1960), Cellino and Graf (1999) and Peng *et al.* (2001).

On the other hand, some investigators believe that there is more energy loss in the process of suspension and that there is also an increased viscous *resistance*. Amongst those who subscribe to this theory—and whose experiments support it—are: Ippen (1973), Imamato *et al.* (1977) and Lyn (1991).

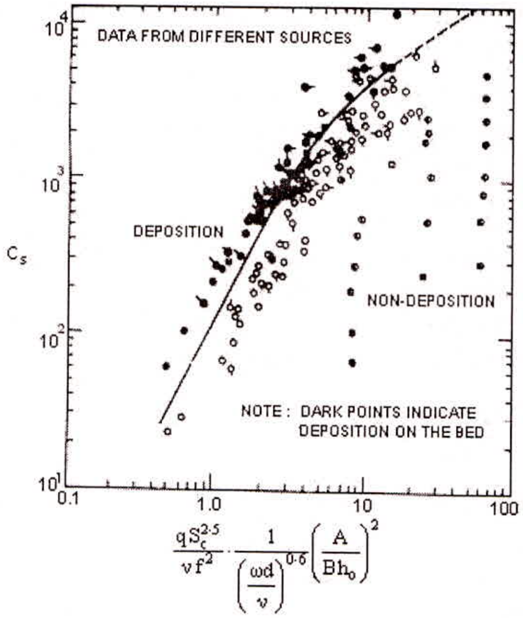

Fig. 2: Criteria for Deposition of Fine suspended Sediment in Lined Canals (Arora *et al.* 1984)

After a thorough examination of all available data and his own experiments, Khullar (2002) categorized channels into two different types: Rigid Boundary (RB) channels, Closely Packed Non-Alluvial and Alluvial (CPNAA) channels. The first category is channels with concrete or cement plaster lining and the second category are those with closely packed sand and gravel on the bed, which may or may not be moving. Khullar (2002) found that the friction factor invariably decreased in CPNAA channels with a flat bed, primarily because of the change in the composition of the surface layer due to the deposition of the fine sediment in the interstices. In case of RB channels Khullar (2002) found that,

$$\frac{f}{f_o} \leq 1.0 \text{ when } C_s^{1/8}\left(\frac{u_* d}{\nu}\right) \leq 0.65 \qquad \dots (13)$$

$$\frac{f}{f_o} > 1.0 \text{ when } C_s^{1/8}\left(\frac{u_* d}{\nu}\right) > 0.65 \qquad \dots (14)$$

Here f_o is the friction factor for clear water flow, f is the friction factor for sediment-laden flow and u_* is the shear velocity. In other words, the friction factor decreases for $C_s^{0.125}$ $(u_*d/\nu) \leq 0.65$ and increases when the value of this parameter is greater than 0.65.

Friction Factor Predictors

By analyzing a vast amount of data from different sources, Khullar (2002) obtained the following relationship for the decrease of friction factor in CPNAA channels due to the presence of fine sediment in suspension,

$$1-\frac{f}{f_o} = 10^{-5}\ (s-1)\frac{C_s\ \omega}{U\ S} \qquad \dots (15)$$

in which s = relative density of the sediment. The close agreement of experimental data with Eqn. (15) is shown in Figure 3.

As already mentioned, the friction factor may increase or decrease in the presence of sediment in case of rigid boundary channels depending on the value of $C_s^{0.125}$ (u_*d/γ). Khullar (2002) obtained the following equations for f/f_o based on analysis of available data,

For $C_s^{0.125}\left(\frac{u_* d}{\nu}\right) > 0.65$ (*i.e.* when $f/f_o > 1.0$)

$$\frac{f}{f_o} = \exp\left(8 * 10^{-6}(s-1)\frac{C_s\omega}{US}\right) \qquad \dots (16)$$

For $C_s^{0.125}\left(\frac{u_* d}{\nu}\right) \leq 0.65$ (*i.e.* when $f/f_o \leq 1.0$)

$$1-\frac{f}{f_o} = 10^{-12}\left[(s-1)\frac{C_s\omega}{US}\right]^3 + 10^{-8}\left[(s-1)\frac{C_s\omega}{US}\right]^2 - 5\times 10^{-5}\left[(s-1)\frac{C_s\omega}{US}\right] \qquad \dots (17)$$

Figure 4 shows Eqn. (17) along with the data used in developing it.

It is noticed that the reduction in f in rigid-bed channels is more than in CPNAA channels for the same value of $(s-1)\left(\frac{C_s\omega}{US}\right)$. Equations (13) to (17) are useful tools in the design of lined canals or tunnels carrying fine sediment in suspension. The influence of the size of the wash material needs to be investigated further, because Eqns. (13) to (17) are based on data over a small range of size of wash load.

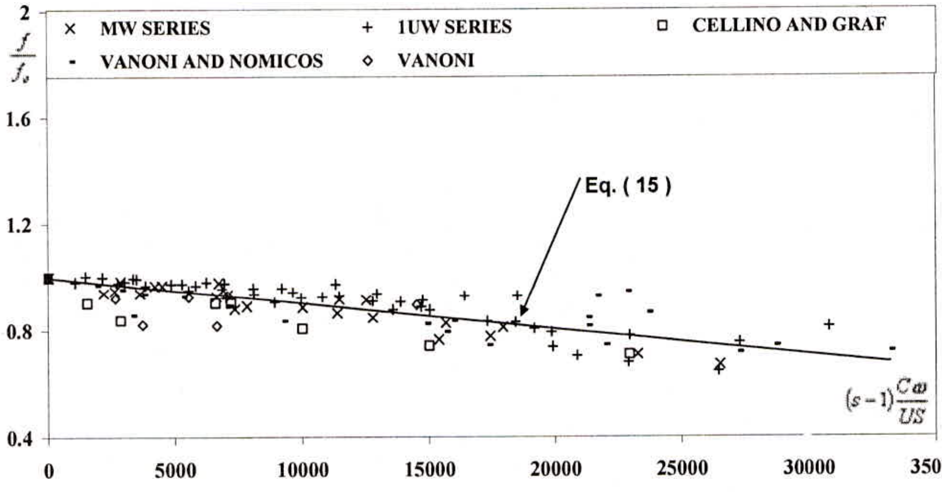

Fig. 3: Variation of $\frac{f}{f_o}$ with $(s-1)\frac{C_s\omega}{US}$ for CPNAA Channels (Khullar, 2002)

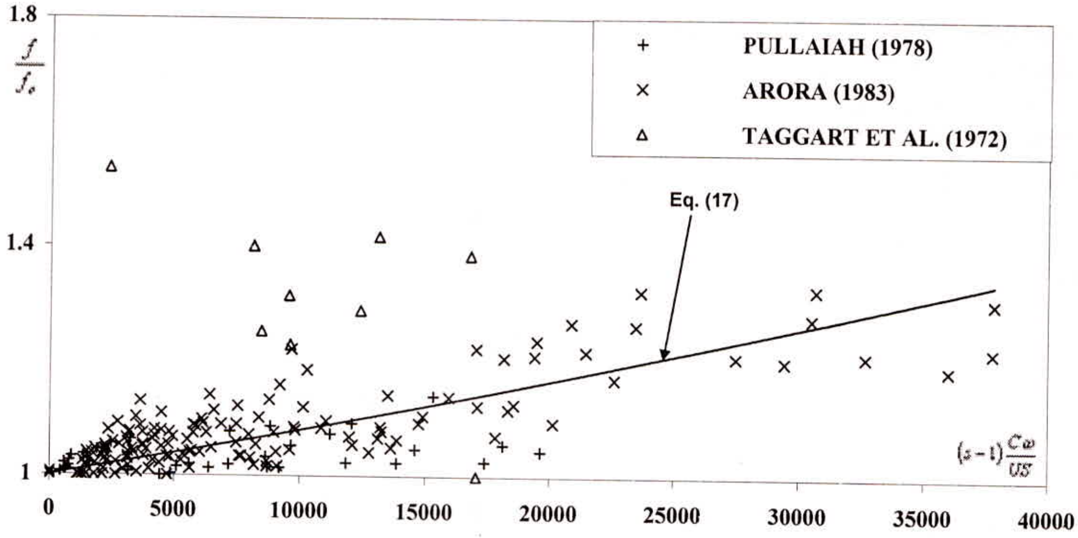

Fig. 4: Variation of $\frac{f}{f_o}$ with $(s-1)\frac{C_S\omega}{US}$ for $C_S^{0.125}\left(\frac{Ud}{v}\right)$ greater than 0.65 in Rigid-Bed Channels (Khullar, 2002)

SEDIMENT EXTRACTION

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—as determined from Figure 2—the excess load will have to be removed. Such extraction devices are located a short distance downstream of the head regulator of the canal and upstream of the canal reach in which the sediment load is to be reduced to a desired value. 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.

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; see Figure 5.

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).

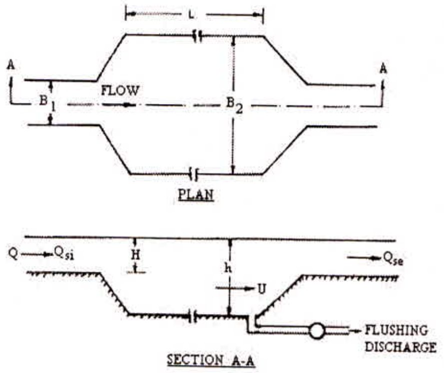

Fig. 5: Definition Sketch of a Settling Basin

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,

$$\eta = 102.5\left(1-\exp\left(-0.3\frac{A_b}{A_a}\right)\right)\left(1-\exp\left(-0.1\frac{L}{h}\right)\right)\left(1-\exp\left(-0.42\frac{\omega}{u_*}\right)\right) \quad \dots (18)$$

Equation (18) 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. Equation (18) is able to estimate η values with a maximum error of about ±25%.

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

$$\frac{\eta_f}{\eta} = 1 - 0.12 Q_f^{-0.105} \left(\frac{\omega}{u_*} \right)^{0.312} \quad \ldots (19)$$

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. The error in estimation of efficiency from Eqn. (19) is generally less than ±8%.

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) and Athar *et al.* (2003). 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.*, 2003). However, use of these extractors is limited to small size power and irrigation canals or pipes as the circular chamber having diameter about five times that of the inflow channel width is needed for efficient extraction.

CONCLUSIONS

Hydroelectric power development requires the construction of barrages or dams across rivers as well as canals to carry the water to the turbines. In case of boulder, gravel and alluvial rivers the design of the reservoir and the canal requires consideration of the sediment brought in by the river and that entering the canal. Lined canals or tunnels are invariably used as the water conductor system in hydroelectric projects.

The basic equations governing morphological changes in rivers due to the construction of barrages and dams are written down and reference made to the use of tools to solve these equations to compute sedimentation in reservoirs. Methods available for estimation of sediment yield in Indian catchments are explained. Lined canals or tunnels have an upper limit of transport of fine sediment in suspension and Figure 2 is an excellent tool for determining that limit. In case the incoming load exceeds the limiting load, structures like settling basins or vortex chamber extractors will need to be built to remove the excess sediment load. Equations (17) and (18) enable calculation of the efficiency of settling basins. Vortex chamber type extractors provide high efficiency of sediment removal at small flushing discharges but have the limitation of being applicable when in-flow channel is small in size.

The friction factor may increase or decrease in the presence of suspended sediment. Equations (13) and (14) provide the criteria for assessing whether a decrease or an increase takes place. Equations (15) to (17) serve as predictors for friction factors required for use in the design of lined canals carrying fine sediment in suspension.

REFERENCES

Arora, A.K., Garde, R.J. and Ranga Raju, K.G. (1984). "Criterion for deposition of sediment transported in rigid boundary channels". *Proc. Int. Conf. on Hydr. Str. In: Water Resour. Engrg.*, Channels and Channel Control Struct., Southampton, U.K.

Atkinson, E. (1992). "*The design of sluiced settling basins—a numerical approach*". Rep OD124, Overseas Development Unit, HR Wallingford, U.K.

Athar, M., Kothyari, U.C. and Garde, R.J. (2002). "Sediment removal efficiency of vortex chamber type sediment extractor". *J. of Hydr. Engrg., ASCE,* 128(12), 1051–1059.

Bagnold, R.A. (1966). "An approach to the sediment transport problem from general Physics", Professional Paper 422–1, USGS, Washington DC.

Borland, W.M. and Miller, C.R. (1958). "Distribution of sediment in large reservoirs". *J. of Hydr.s Div., ASCE*, 84(2).

Brune, G.M. (1953). "Trap efficiency of reservoirs", *Trans. AGU.* 14(3).

Celik, I. and Rodi, W. (1991). "Suspended sediment transport capacity for open channel flows". *J. of Hyd. Engrg., ASCE*, 117(2), pp. 191–2004.

Cellino, M. and Graf, W.H. (1999). "Sediment-laden flow in open channels under non-capacity and capacity condition". *Journal of Hydraulic Engineering, ASCE*, 125(5), pp. 455–462.

Cecen, K. and Bayazit, M. (1975). "Some laboratory studies of sediment controlling structures". *Proc. 9th Congress of ICID, Moscow*, pp. 107–111.

Curi, K.V., Esen, L.L. and Velioglu, S.G. (1979). "Vortex type solid-liquid separator". *Progress in Water Technology*, 7(2), pp. 183–190.

Dobbins, W.E. (1944). "Effect of turbulence on sedimentation". *Trans ASCE*, 109, pp. 629–653.

Dongre, N.B. (2002). "Settling basin design". M. Tech Thesis, Dept. of Civil Engineering, Indian Institute of Technology, Roorkee, India.

Dhruva, Narayan and Bam, Babu. (1983), "Estimates of soil erosion in India". *J. of Irrig. and Darain. Engrg.*, ASCE, Vol. 109. No. 3.

Garde, R.J. and Kothyari, U.C. (1986). "Erosion in Indian catchments". *Proc. 3rd Int. Symposium on River Sedimentation*, Jackson (Miss), U.S.A.

Garde, R.J. and Ranga Raju, K.G. (2000). "Mechanics of sediment transportation and alluvial stream problems". *Third edition, New Age International Publisher, Ltd.*, New Delhi, India.

Hydraulic Research Wallingford. (1996). "Measuring and predicting reservoir volume change due to sedimentation". *User Manual*, RESSAS, HR Wallingford, Oxon, U.K.

Imamato, H., Asano, T. and Ishigaki, T. (1977). "Experimental investigations of a free surface shear flow with suspended sand grains". *Proc. 17th Congress of IAHR*, Baden - Baden, A4.

Ippen, A.T. (1973). "Transport of suspended sediment". *Proc. Int. seminar on hydraulics of alluvial streams, IAHR*, New Delhi.

Itakura, T. and Kishi, T. (1980). "Open channel flow with suspended sediments". *J. of Hydr. Div., ASCE.* 106(8).

Julien, P.Y. (1986). "Concentration of very fine silts in steady vortex". *J. of Hydr. Res., IAHR*, 24(4), pp. 255–264.

Khullar, N.K. (2002). "Effect of wash load on transport of non-uniform sediments". Ph.D. Thesis Dept. of Civil Engineering, Indian Institute of Technology, Roorkee, India.

Krishnappan, B.G. and Snider, N. (1977). "*Mathematical modeling of sediment-laden flows in natural streams*". Scientific series No. 81, Inland Water Directorate, Canada Centre for Inland Waters, Burlington, Ontario, Canada.

Kothyari, U.C., Jain, M.K. and Ranga Raju, K.G. (2002). "Estimation of temporal variation of soil erosion and sediment yield using GIS". *Hydrological Sciences Journal, IAHS*, 47(5), pp. 693–706.

Lyn, D.A. (1987). "Unsteady sediment transport modeling". *J. of Hydr. Div., ASCE*, 113(1), pp. 16–28.

Lyn, D.A. (1991). "Resistance in flat-bed sediment-laden flow". *J. of Hydr.c Engrg., ASCE*, 117(1), pp. 94–114.

Mashauri, D.A. (1986). "Modelling of vortex settling basin for primary classification of water". Ph.D. Thesis, Tamperi University of Technology, Finland, pp. 217.

Nalluri, C. and Spaliviero, F. (1998). "Suspended sediment transport in rigid boundary channels at limit deposition". *Water Science and Technology*, 37(1), pp. 147–154.

Peng, L, Chen, L. and Huang, J. (2001). "Study of the structure of flow in open channel with suspended sediment". *Proc. XXIX Congress of IAHR*, Beijing, China.

Ram Babu, K.G. Tejwanl, M.C. Agarwal and Subhash, Chandra (1978). "Rainfall, erosion potentlonal and map of India". *ICAR Bull*, No. 2, Dehradun.

Ranga Raju, K.G. and Kothyari, U.C. (2005). "Sediment Management in Hydraulic Projects". *Int. Journal for Sediment Research*, Vol. 20, No. 1, pp. 52–61.

Ranga Raju, K.G., Kothyari, U.C., Srivastav, S. and Saxena, M. (1999). "Sediment Removal Efficiency of Settling Basins". *J. of Irrig. and Drain. Engrg., ASCE*, 125(5), pp. 308–314.

Sumer, M.S. (1977). "Settlement of solid particles in open channel flow". *J. of Hydr. Div., ASCE*, 103(11), pp. 1323–1337.

Schrimpf, W. (1991). "Discussion of design of settling basins by R.J. Garde, K.G. Ranga Raju and A.W.R. Sujudi". *J. of Hydr. Res., IAHR*, 29(1), pp. 136–142.

Singh, A.K., Kothyari, U.C. and Ranga Raju, K.G. (2004). "Rapidly varying unsteady flows in alluvial rivers". *J. of Hydr. Res., IAHR*, 42(5), pp. 473–486.

Vanoni, V.A. (1946). "Transportation of suspended sediment by water". *Trans. of ASCE*, 111, pp. 67–133.

Vanoni, V.A. and Nomicos, G.N. (1960). "Resistance properties of sediment-laden streams". *Trans. of ASCE*, 125, pp. 1140–1175.

Walling, D.E. (1994). "Erosion and sediment in a changing environment". Proc. of the Int. Symp., East-West, North-South Encounter on the State-of-the art in River Engineering Methods and Design Philosophies, St. Petersburg, Russia.

Zhau, Z., Wang, C. and Hou, J. (1989). "Model study on flushing cone with strong spiral flow". Proc. Fourth Int. Symp. on River Sedimentation, Beijing, China, pp. 1213–1219.