Proceedings of the Ninth International Symposium on River Sedimentation
October 18 – 21, 2004, Yichang, China

SEDIMENT MANAGEMENT IN HYDROELECTRIC PROJECTS

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Abstract: Withdrawal of water from a river into a canal involves the construction of a barrage or a dam across the river depending on whether the river is perennial or not. 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 basic equations concerning morphological changes in such rivers are discussed with particular reference to computation of reservoir sedimentation. The hydraulics of lined canals carrying wash load is examined from the point of view of limiting transport capacity and changes in frictional resistance. Lastly, the methods of design of sediment extraction devices like settling basins and vortex chambers are presented.

Keywords: Canal, Flow Resistance, Friction Factor, Reservoir and Settling Basin

1 INTRODUCTION

Rivers have sustained human civilizations for several centuries. The needs of drinking water, irrigation, electric power and navigation are often met by river systems. Reservoirs and/or canals have to be built to cater to some of the above demands. Hydropower development generally involves the construction of a reservoir 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.

Alluvial rivers pose several challenging problems in the design of reservoirs built on them and of 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.

2 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.

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 (Fig. 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.

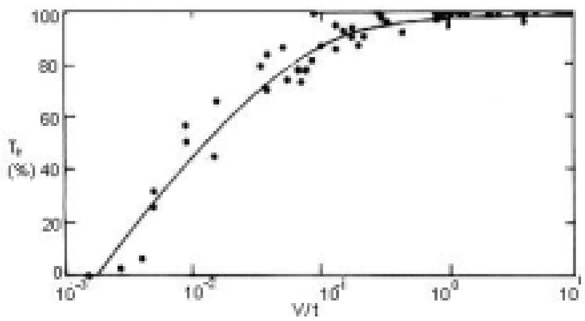

Fig. 1 Trap Efficiency of Reservoirs (Brune, 1953)

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

$$\frac{\partial Q}{\partial x} + P\frac{\partial z}{\partial t} + B\frac{\partial h}{\partial t} = 0 \tag{1}$$

Flow Momentum Equation

$$\frac{\partial Q}{\partial t} + \frac{2Q}{A}\frac{\partial Q}{\partial x} - B\frac{Q^2}{A^2}\frac{\partial h}{\partial x} - \frac{Q^2}{A^2}\left.\frac{\partial A}{\partial x}\right|_{h=\text{const.}} + gA\frac{\partial h}{\partial x} + gA\frac{\partial z}{\partial x} + gAS_f = 0 \tag{2}$$

and

Sediment Continuity Equation

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

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 Eqs. (2) and (3) are discussed by Garde and Ranga Raju (2000). Some of the more commonly used models for the solution of Eqs. (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.

3 DESIGN OF LINED CANALS

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:

①Sediment carrying capacity of Lined Canals

②Resistance 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.

3.1 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) and Nalluri and Spaliviero (1998) are superior to the others.

3.1.1 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 Fig. 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, ν 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, γ_f being the specific weight of the fluid and γ_s the specific weight of the sediment. The curve drawn on Fig. 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 Fig. 2) to be incapable of transporting the expected load without deposition, a steeper slope – which indicates no deposition on Fig. 2– needs to be provided.

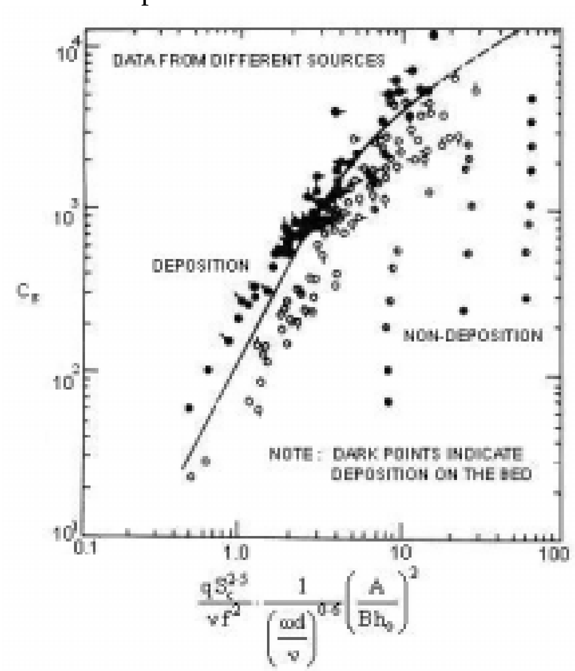

Fig. 2 Criteria for Deposition of Fine suspended Sediment in Lined Canals (Arora *et al*., 1984)

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 Fig. 2 can be used also for the determination of the limiting concentration of wash load carried by alluvial channels with relatively coarse bed material.

3.1.2 Nalluri and Spaliviero method

The equation for limiting volume concentration C_{sl} in rigid boundary rectangular channels as per Nalluri and Spaliviero (1998) is

$$\frac{U}{\sqrt{\left(\Delta\gamma_s / \rho_f\right) d}} = 3.32 C_{sl}^{0.12} \left(\frac{d}{h}\right)^{0.28} f^{-0.14} \tag{4}$$

Here U is the average velocity of flow and ρ_f is the mass density of the fluid. Eq. (4) was also found (Khullar, 2002) to be applicable to wash load transported in an alluvial channel.

3.2 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).

After a thorough examination of all available data and his own experiments, Khullar (2002) categorized channels into two different types:

① Rigid boundary (RB) channels

② 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

$$\frac{f}{f_o} \le 1.0 \qquad \text{when} \quad C_s^{1/8}\left(\frac{u_* \, d}{\nu}\right) \le 0.65 \tag{5}$$

$$\frac{f}{f_o} > 1.0 \qquad \text{when} \quad C_s^{1/8}\left(\frac{u_* \, d}{\nu}\right) > 0.65 \tag{6}$$

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 $C_s^{0.125}$ $(u_* d/\nu) \le 0.65$ and increases when the value of this parameter is greater than 0.65.

3.2.1 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:

$$1 - \frac{f}{f_o} = 10^{-5} \, (s-1)\frac{C_s \, \omega}{U \, S} \tag{7}$$

in which s = relative density of the sediment. The close agreement of experimental data with Eq. (7) is shown in Fig. 3.

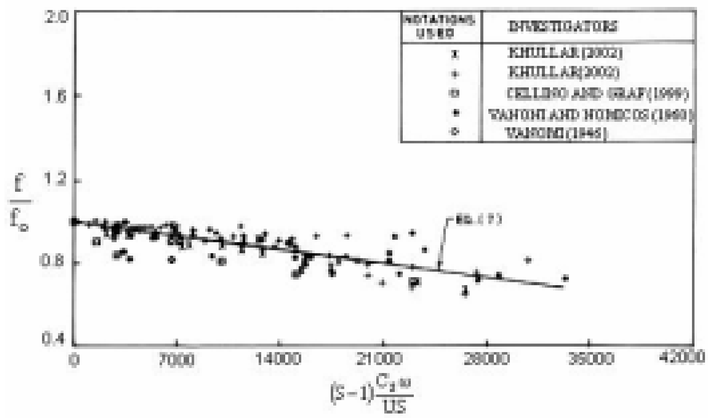

Fig. 3 Variation of $\frac{f}{f_o}$ with $(s-1)\frac{C_s \omega}{US}$ for CPNAA Channels (Khullar, 2002)

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

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

$$\frac{f}{f_o} = \exp\left(8\times10^{-6}(s-1)\frac{C_s\omega}{US}\right) \tag{8}$$

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

$$1 - \frac{f}{f_o} = 10^{-12}\left[(s-1)\frac{C_s\omega}{US}\right]^3 + 10^{-8}\left[(s-1)\frac{C_s\omega}{US}\right]^2 - 5\times10^{-5}\left[(s-1)\frac{C_s\omega}{US}\right] \tag{9}$$

Fig. 4 shows Eq. (8) along with the data used in developing it. The relation for f/f_o, when there is a decrease in friction factor is shown in Fig. 5.

It may be seen that the reduction in f in rigid-bed channels is more than in CPNAA channels for the same value of (s-1)$\left(\frac{C_s\omega}{US}\right)$. Eqs. (7) to (9) are useful tools in the design of lined canals carrying fine sediment in suspension. The influence of the size of the wash material needs to be investigated further, because Eqs. (7) to (9) are based on data over a small range of size of wash load.

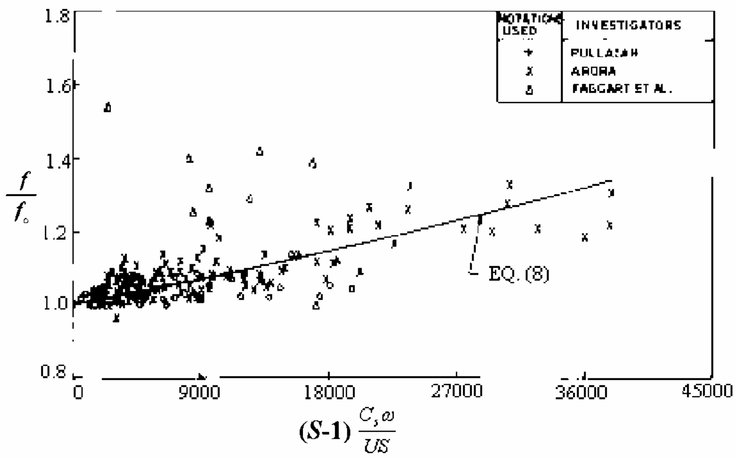

Fig.4 Variation of $\frac{f}{f_o}$ for $C_s^{0.125}\left(\frac{Ud}{\nu}\right)$ Greater Than 0.65 in Rigid-Bed Channels (Khullar, 2002)

4 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 Fig. 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.

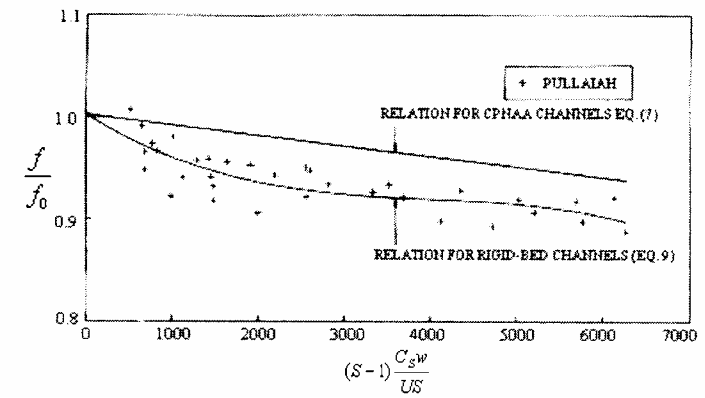

Fig.5 Variation of $\dfrac{f}{f_o}$ for $C_s^{0.125}\left(\dfrac{Ud}{\nu}\right)$ Less Than 0.65 in Rigid-Bed Channels (Khullar, 2002)

4.1 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; see Fig. 6.

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).

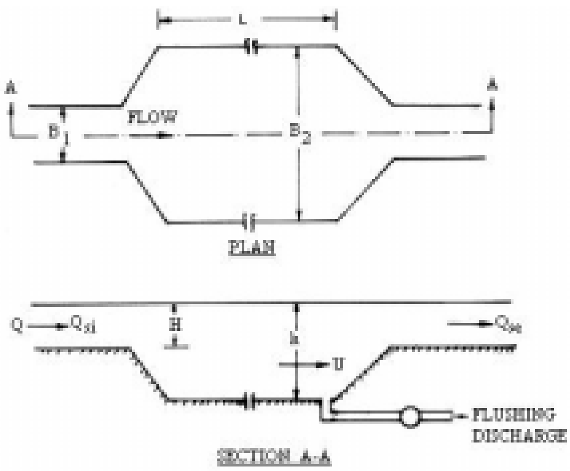

Fig. 6 Definition Sketch of a Settling Basin

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:

$$\eta = 102.5\left(1-\exp\left(-0.3\frac{A_b}{A_a}\right)\right)\left(1-\exp\left(-0.1\frac{L}{h}\right)\right)\left(1-\exp\left(-0.42\frac{\omega}{u_*}\right)\right) \qquad (10)$$

Eq. (10) 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. Fig. 7 shows that Eq. (10) is able to estimate η values with a maximum error of about $\pm$25%.

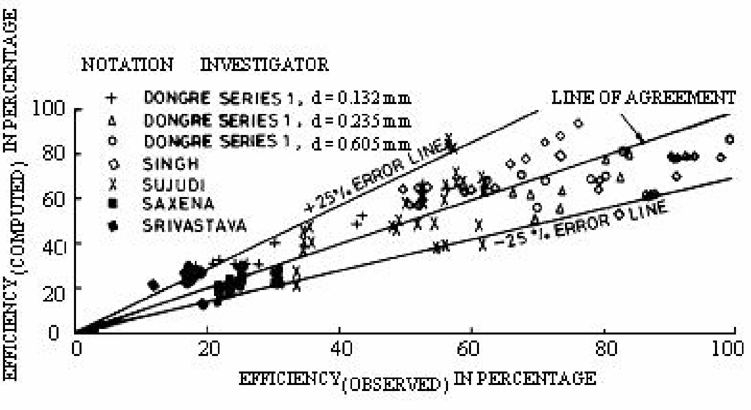

Fig. 7 Comparison of Efficiency$_{(Observed)}$ With Efficiency$_{(Computed)}$ Using Eq. (10)

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

$$\frac{\eta_f}{\eta} = 1 - 0.12 Q_f^{-0.105} \left(\frac{\omega}{u_*} \right)^{0.312} \tag{11}$$

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. 8 shows that the error in estimation of efficiency from Eq. (11) is generally less than $\pm$8%.

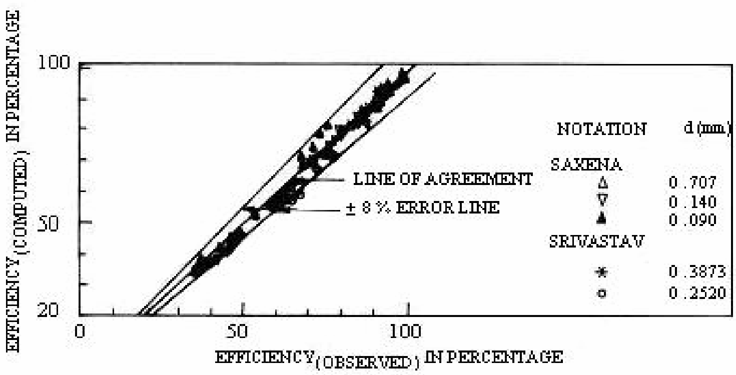

Fig. 8 Comparison of Efficiency$_{(Observed)}$ With Efficiency$_{(Computed)}$ Using Eq. (11) (Basin With Flushing)

4.2 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*. (1997) 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.

5 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 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. Lined canals have an upper limit of transport of fine sediment in suspension and Fig. 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. Eqs. (10) and (11) 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. Eqs. (5) and (6) provide the criteria for assessing whether a decrease or an increase takes place. Eqs. (7) to (9) serve as predictors for friction factors required for use in the design of lined canals carrying fine sediment in suspension.

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