SEDIMENTATION OF RIVERS, RESERVOIRS AND CANALS

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Contents

Summary

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. Depending on the extent of detail proposed to be gone into, the designer may need only information on the gross sediment yield from the catchment on the one extreme and complete information on the amount of wash load and the size distribution of the materials transported as bed load and in suspension on the other. All these aspects are discussed in this chapter.

1. Introduction

Rivers have sustained human civilizations for several centuries. The needs of drinking water, irrigation, electrical power and navigation are often met by river systems. Rivers have also been used as sinks for domestic and industrial wastes in their treated or untreated forms. Reservoirs and/or canals have to be built to cater to some of the above demands.

A canal is invariably required to carry river water to irrigate agricultural lands; water could be diverted into a canal from a large-capacity reservoir or a small diversion structure built on the river. 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 disturb 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 chapter. The contents are influenced to a significant extent by the Indian practice in handling these problems.

1.1. Storage and Diversion Structures

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 less disturbance to river regime than those which 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 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.

2. Sediment Problems

Several problems related to the presence and movement of sediment need to be understood and tackled for making comprehensive designs of canals and reservoirs (see *Sediment Exclusion at Intakes*).

2.1. Sediment Problems Related to Canal Design

Water diverted into a canal from a large capacity reservoir may be sediment-free or it may contain fine sediment in suspension. If the canal boundary is non-erodible, i.e. it is a lined canal; the designer has to ensure that the anticipated load entering the canal is transported downstream without getting deposited on the bed.

In other words, the carrying capacity of the canal should be larger than the amount of incoming wash load. If the boundary is erodible, i.e. it consists of sand and gravel, an additional design requirement is that the shear stress on the boundary is not large enough to cause movement of these particles. The method given by Lane offers a complete solution to the latter problem.

The design of an unlined canal carrying sediment-laden flow requires the solution of the following three equations:

- Relation for stable perimeter
- Resistance relationship
- Sediment transport relationship.

One can use the foregoing equations to determine the bed width, *b*, the depth, *h* and the longitudinal slope, *S*.

The observed perimeter of stable canals with sandy bed and cohesive banks is not much different from that given by Lacey, viz.

$$P = 4.75\sqrt{Q} \quad (1)$$

in which Q is the discharge expressed in m^3/s and P is the wetted perimeter expressed in meters. As such, Eq. (1) may be used with confidence in stable channel design.

Alluvial canals are generally designed to be in the ripple and dune regime and thus the range of variation of roughness coefficient expected in canals is smaller than in rivers in which flat bed and anti-dunes may also occur particularly at steep slopes. One would thus expect less error in the resistance coefficient for canals computed from the available relationships because of the narrow range of bed forms likely to occur.

Any of the well known resistance relationships, e.g. those by Engelund, Ranga Raju, Kishi-Kuroki (Task Committee, JSCE), Karim-Kennedy, Brownlie and Van Rijn, may be used for estimation of the roughness coefficient. Most of the foregoing relationships are discussed by Garde and Ranga Raju.

There are a large number of *sediment transport* relationships to choose from for the design of stable canals and some of these are discussed later in the chapter.

Yet another aspect of practical importance is sediment extraction from the canal when the incoming load is in excess of what can be transported with the available slope. Certain coarse sizes would have to be excluded also, because of the harm they may cause to the turbine blades. It is generally intended to prevent sediment coarser than 0.20 mm from entering the turbine. The design of a settling basin which reduces the sediment load is also discussed later.

2.2. Sediment Problems Related to Reservoir Design

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 and Miller) from which the reduction in storage capacity at various elevations can be worked out. The relationship given by Brune for trap efficiency T_e as a function of the ratio of storage capacity C to Annual Water Inflow volume I should be deemed to be a satisfactory tool for the determination of trap efficiency, as shown in Figure 1. A method of estimation of sediment yield is discussed later; use of this method 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.

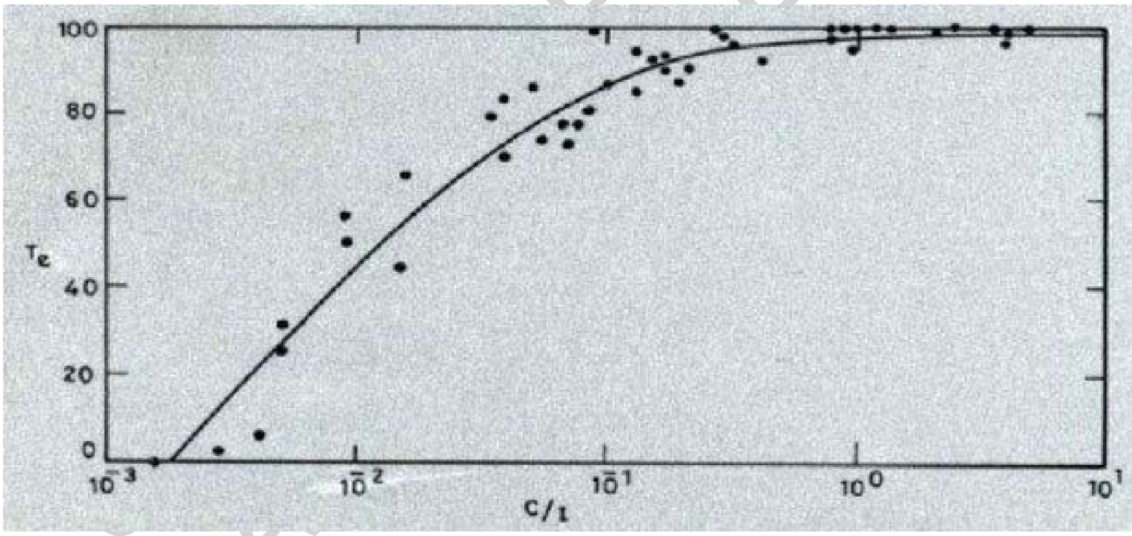

Figure1. Trap efficiency of reservoirs

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

Flow continuity Equation

$$\frac{\partial Q}{\partial x} + P\frac{\partial z}{\partial t} + B\frac{\partial h}{\partial t} = 0 \qquad (2)$$

Flow momentum Equation

$$\frac{\partial Q}{\partial t}+2\frac{Q}{A}\frac{\partial Q}{\partial x}-B\frac{Q^2}{A^2}\frac{\partial h}{\partial x}-\frac{Q^2}{A^2}\frac{\partial A}{\partial x}\Big|_{h=const.}+gA\frac{\partial h}{\partial x}+gA\frac{\partial z}{\partial x}+gAS_{\mathrm{f}}=0 \qquad (3)$$

Sediment continuity equation

$$\frac{\partial Q_{\mathrm{b}}}{\partial t}+\frac{\partial Q_{\mathrm{s}}}{\partial x}+P(1-\lambda)\frac{\partial z}{\partial t}+BC_{\mathrm{s}}\frac{\partial h}{\partial t}+A\frac{\partial C_{\mathrm{s}}}{\partial t}=0 \qquad (4)$$

Where z = Bed elevation
B = Water surface width
x = Distance along the flow direction
t = Time
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 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.

2.3. Scope of the Chapter

Based on the analysis of sediment problems related to canals and reservoirs, the following aspects related to sediment load and its estimation are discussed in the following sections of this chapter:

- Estimation of Sediment Yield from Catchments
- Carrying Capacity of Lined Channels and Sediment Control
- Sediment Load Calculations for Uniform Materials
- Fraction-wise Calculation of Sediment Load
- Non-equilibrium Effects on Sediment Transport

Several important practical problems like density currents and their venting, and flushing of reservoirs are not addressed in this chapter.

3. Estimation of Sediment Yield

It is reported that the surface of the earth is eroded at an average rate of 30mm per 1000 years. Naturally this erosion rate varies from year to year and from region to region. Table 1 due to Chorley gives the average erosion rates in different continents.

Continent	Area in Million km^2	Erosion rate in tons/km^2/year
Africa	29.81	72.2
Asia	44.89	208.0
Australia	7.88	43.4
North and Central America	20.44	113.0
South America	17.98	148.0
Europe	4.67	75.0

Table 1: Average Erosion Rates in Different Continents

While Table 1 gives the erosion rates for continents as a whole, the sediment yield from individual river catchments varies from as little as 1ton/km^2/year to as much as 50 000 tons/km^2/year. The various factors which affect sediment yield are discussed by Walling.

Empirical prediction equations are often used in the estimation of annual sediment yield. Equations like the Universal Soil Loss Equation (USLE) are used to calculate the soil loss due to sheet erosion from small experimental plots.

The USLE is not suited for the estimation of sediment yield from large catchments. Garde and Kothyari analyzed data from Indian catchments of small to large sizes, and proposed the following equation for sediment yield:

$$V_s = 0.02\, p^{0.60} F_e^{1.7}\, \bar{S}^{0.25}\, D_d^{0.10} \left(\frac{P_{max}}{p} \right)^{0.19} \qquad (5)$$

Here V_s is the annual sediment yield expressed in centimeters of absolute volume, $\bar{S}$ is the average slope of the catchment, p is the average annual precipitation expressed in centimeters and D_d is the drainage density expressed in km^{-1}. F_e is the erosion factor, defined as

$$F_e = \frac{1}{a}\left[0.80 a_A + 0.60 a_G + 0.30 a_F + 0.10 a_W\right]$$

in which a is the total catchment area out of which a_A = arable area, a_G = grass land area. a_F = forest area and a_W = waste land area. The range of data used in developing Eq. (5) is as given below:

a = 347 km^2 to 132 090 km^2
F_e = 0.28 to 0.79
D_d = 0.04 to 0.31 km^{-1}
$\bar{S}$ = 0.005 to 0.045

p = 38.6 cm to 455.6 cm.

The areas required for calculation of F_e from Eq. (6) may be obtained from the soil cover map of the catchment. A map giving the drainage network in the catchment will have to be used to determine D_d.

The significant features of Eq. (5) are that it takes into account practically all the factors which affect sediment yield and that it is derived using field data covering a wide range of pertinent variables.

As such, the equation is recommended for use in preliminary estimates of sedimentation rates in reservoirs following the procedure outlined in Section 2.2.

4. Carrying Capacity of Lined Canals and Sediment Control

Power generation channels are invariably designed and built as lined canals. Increasingly in recent years, lined canals are being preferred, even for irrigation channels, on account of low seepage losses from them.

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 can damage the lining.

Arora 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 parts per million by volume, $q = Q/B$, f_b is the Darcy-Weisbach resistance coefficient of the bed, h_0 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 and $\Delta\gamma_S$ is the difference in specific weights of the sediment and fluid, γ_f being the specific weight of the fluid. 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 which can be safely carried without deposition by the available slope. A *settling basin* offers a good solution for the removal of excess load in suspension. The settling basin is also well suited to remove all sediment coarser than 0.20mm - a requirement in the case of canals carrying water to hydro-electric power station turbines.

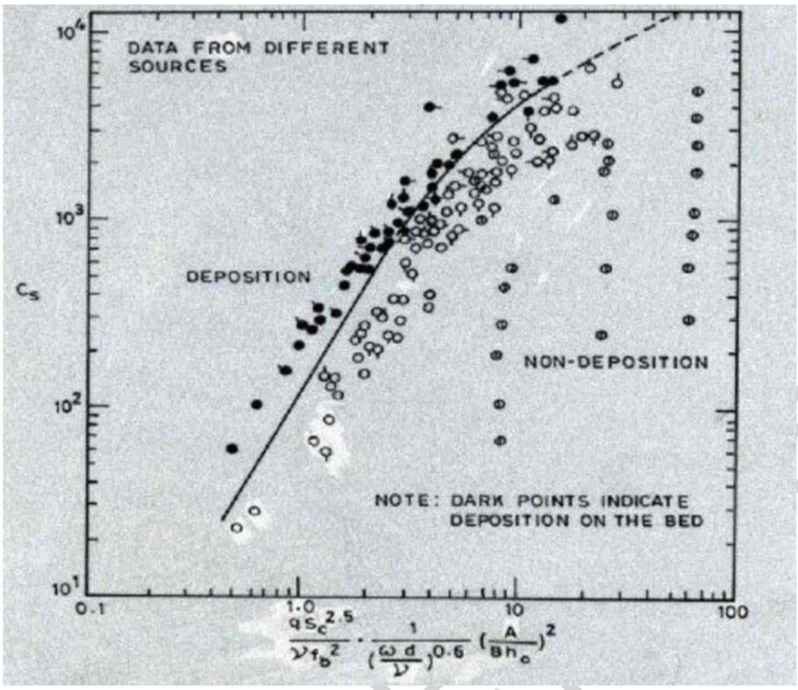

Figure 2. Criterion for deposition of fine suspended in lined canals

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Biographical Sketch

K.G. Ranga Raju (born 1942) is a Professor of Civil Engineering at the University of Roorkee, India. He is author of two text books and the author of a chapter of an IAHR monograph. His research interests include Fluvial Hydraulics, Industrial Aerodynamics, Hydraulic Structures and Hydrometry, and he has published a large number of research papers in various journals. He is the recipient of several awards, including the “*A.T. Ippen award of IAHR*” in 1985 for his “many contributions to the understanding and formulation of river processes”. Dr. Ranga Raju is member of the editorial committees of many scientific journals.