SEDIMENTATION OF LAKES

Dr. A. R. Senthil kumar
Scientist-E1, NIH, Roorkee

Four Days Training Course on
HYDROLOGICAL INVESTIGATIONS FOR CONSERVATION AND MANAGEMENT OF LAKES
(15-18 January, 2013)

SEDIMENTATION OF LAKES

A. R. Senthil kumar
Scientist – E1
Surface Water Hydrology Division
National Institute of Hydrology, Roorkee-247 667 (Uttarakhand)
E-mail: arsk@nih.ernet.in

INTRODUCTION

Sedimentation is one of the serious problems of many lakes causing reduction in lake capacity and useful life of the lake. As such the knowledge of lake sedimentation process is very essential for control and management of the lake sedimentation. It is also essential for understanding the ecological behaviour of lakes. Although high concentrations of suspended matter may result in low primary production because of restricted light penetration, supply of excess nutrients to lake through sediments however, increases its productivity. The availability of dissolved oxygen in lakes may be limited due to high sediment oxygen demand. Benthos and fish are affected not only by the suspended sediments but also by the modification of habitat caused by depositional sediments. Sedimentary processes may also cause changes in the lake basin forms. The sediment character controls the chemical composition of the lake water. So, the interaction of sediments with the lake water, both within the water column and at the bed of the lakes, controls the quality of the surface water. Sediment also contains biological life. It is a substrate for bacterial activity. Nature of sediments coming to a water body depends upon the rock type in the drainage basin. Siltation rates are mainly dependent upon conditions in the drainage area. Other factors include morphological and hydrodynamic factors. Effects of drainage basin are mainly due to morphology, climate and land use. There are three main sources of sediments for lakes. Water and wind are the main natural agents which bring sediments into the lake. Organic matter produced in the lake is an internal source. Besides, there is also a problem of re-suspended bottom material.

The bed load brought by the river is initially deposited preferably on shallow water near the shores. Fine particles have low settling velocities and are kept in suspension by the water motion. Fine material from the lake bottom is eroded and brought into suspension by influence of waves and currents. The shallow bottoms from which fine loose material is stirred up at every storm and where there are no extended periods of deposition are called erosion bottoms. Transportation bottoms prevail where fine material is deposited but where erosion takes place during severe storm. Areas where fine material is deposited and erosion never occurs are called accumulation bottom. In shallow lakes there are no accumulation bottoms where material can deposit. The bottom sediments close to the shores as well as in the central parts of such lakes are a mixture of fine and coarse material.

Re-suspension of the settled sediments is basically governed by the balance between hydrodynamic forces seeking to move the particle and the stabilizing forces due to gravity. Wave action is the dominating force for re-suspension in lakes. Once the sediments have been re-suspended, they will be redistributed in the lake according to the current pattern and diffusive character of the flow. When the energy level is reduced due to decrease in the wind speed, then the sediments will settle to the bottom. The result is that basically the near shore areas will be void of fine sediments. They will gather in the deeper areas. The shape and depth of the lake basins affect the circulation of water and thus the distribution and deposition of fine sediment particles.

The amount of sediment carried by the incoming river can be measured or estimated from models. However, the amount of locally produced material and re-suspended sediments cannot easily be determined. Long term sedimentation in a lake is best determined by comparing bathymetric maps from different years. The sediment rate over the shorter periods can be determined using sediment traps. These can be bottom placed or floating. To get representative values for the lake, they should be placed on accumulation bottom and for the floating ones, 1-2 m above the bottom. Isotopes techniques are, however, more precise compared to the conventional methods and are hence, becoming popular recently for estimation of sedimentation rates in lakes.

METHODOLOGIES FOR ESTIMATION OF SEDIMENTATION RATE OF LAKES

There are various techniques for the determination of the rate of sedimentation in lake/reservoirs, such as range line method, contour method, sediment balance method, remote sensing techniques and radiometric dating techniques. These are discussed in brief in following sections.

Range Line Method

The range-line method is widely used for medium to large lakes and reservoirs requiring an underwater survey utilising hydrographic surveying methods. In range line method, a number of cross sections, called ranges, of the lakes are surveyed and then it is periodically repeated at the same cross sections. Specific details concerning the method can be found in many references (Vanoni, 1977; and Guy, 1978). Basically, the deposition of sediment during a period is estimated by measuring the depth to bottom (water column) at different locations, which can be compared to a previously constructed map to determine differences in the volume of sediment deposited.

Contour Method

The contour method uses essentially topographic mapping procedures (Wolf, 1974). To apply this method, it is important to have a good contour map of the lake when it is dry (Pemberton and Blanton, 1980).
The procedure for either of the methods involves the determination of bed elevation at many known locations in the lake/reservoir.

Sediment Balance Method

Sediment is carried into a lake by streams and rivers as well as by overland flow entering a lake. Sediment entering a lake may consist of a wide range of sizes, from gravel or boulders to silt and clay particles.

The surest way of obtaining an accurate determination of the amount of sediment being carried to a lake by streams is to measure the flow rate and sediment concentration of the inflowing waters just upstream of the lake. Ordinarily, records of sediment discharge (fine, coarse, suspended, or bedload) are determined on the basis of sample information obtained at non-uniform intervals of time. The information from the sediment samples can be used to estimate the total sediment discharge by developing a relation between the sediment discharge and water discharge, called a sediment transport curve. The sediment outflow from the lake, if any, is computed in the discharges from the lake. The difference of input and output sediment divided by lake area gives the sediment deposition rate.

Remote Sensing Techniques

Remote sensing has several main applications in the assessment of lake/ reservoir sedimentation. Contour maps prepared from aerial photographs can be used to determine sediment volumes provided the water level can be lowered greatly. Aerial photography can be used to trace turbidity plumes, which may help in defining the distribution of sedimentation. Digital image processing of high-resolution satellite data can also be used for lake sedimentation studies. The information of suspended sediments obtained at different times using this technique can be utilised to predict the deposition or settling rate of sediments in the lake.

A comparatively new technique, which is being developed by the U.S. National Ocean Survey, is to use laser hydrography (Enabnit et al., 1979). The airborne laser hydrographic technique uses an aircraft mounted pulsed laser system to collect a swath of discrete soundings along each flight line. It measures water depth exactly like a sonar using light instead of sound.

Radiometric Dating Techniques

Several environmental isotopes including ^{210}Pb, ^{137}Cs and ^{14}C find applications in the estimation of rate of sedimentation in lakes. However, ^{14}C is more useful for paleo-hydrological studies (Kusumgar et al., 1992). Artificial radio-isotopes used for sediment accumulation studies include ^{239}Pu, ^{240}Pu and ^{241}Am. However, for the dating of recent sediments, ^{210}Pb (100 to 150 years BP) and ^{137}Cs (post 1954) are widely used.

TRAP EFFICIENCY

The ratio of sediment retained by the lake to the total inflow of sediment in a given time, expressed in percent, is known as the trap efficiency (TE) of the lake. Based on field data, trap efficiency is found to be a function of various parameters which include ratio of lake capacity to annual inflow, retention period defined as reservoir volume divided daily inflow, sediment and lake characteristics, number and position of outlets. Most of the lakes in the plain area are shallow and the trap efficiency of these lakes is high.

ESTIMATION OF SEDIMENT YIELD

Estimation of sediment load from the catchment of the lake is important to compute the revised capacity of the lakes and to monitor the water quality (Nagy et al., 2002). The estimation of sediment from the catchment has been difficult task due to the complex nature of the sedimentation process. The sedimentation process depends upon the characteristics of basin and river which include climate, land slope and topography, land cover and pattern of land use (Shahin, 1993). Sediment load has been observed to understand sediment process in the watershed as well as to predict the sediment load (Dugan et al., 2009).

Several methods have been proposed to predict sediment load based on the properties of flow and sediment. Models such as black box models, regression based models and physically based models have been developed for computing the sediment yield (Garde and Rangaraju, 1985; Tayfur, 2002; Gao and Pasternack, 2007; Parajuli et al., 2009). During 1945 to 1965, an empirical method for computing the upland soil losses was evolved based on statistical analysis from the experiment conducted from many small plots in the states of USA, which was named as Universal Soil Loss Equation (USLE) (Schwab, et al. 1993). It has been widely used in many countries to estimate the sediment yield from the watersheds despite its simplification of many variables involved. The USLE is given as

$$A = RKLSCP \tag{1}$$

where A is average annual soil loss per unit area, R is rainfall and runoff erosivity index for geographic location, K is soil erodibility factor, L is slope length factor, S is slope steepness factor, C is cover management factor and P is conservation practice factor. USLE predicts average annual gross erosion as a function of rainfall energy. To improve the prediction capability of USLE, the rainfall energy factor is replaced with a runoff factor and this is called as modified universal soil loss equation (MUSLE). Sediment yield prediction is improved because runoff is a function of antecedent moisture condition as well as rainfall energy. MUSLE eliminates the need for delivery ratio and it allows the equation to be applied to individual storm events. The MUSLE is given as

$$Y = 11.8(Qq)^{0.56} KLSCP \tag{2}$$

where Y is the single storm sediment yield (tons), Q is the runoff (m3), q is peak storm discharge (m3/s) and K, L, S, C and P are the standard USLE terms used in equation in (1) (Neitsch et al., 2005).

Physically based semi distributed models such as Soil and Water Assessment Tool (SWAT) and Annualized Agricultural Non Point Source (AnnAGNPS) were developed to estimate the sediment load wherein modified USLE was used for the estimation of sediment yield (Parajuli et al., 2009).

Development of many process-based physical models for computing soil erosion and deposition in the basin are reported in the literature. The models developed are 1D, 2D, 3D considering numerical solution of differential conservation equations of mass and momentum of flow along with sediment mass continuity equation. The models applied to different basins are HEC-6, MOBED, IALLUVIAL, FLUVIAL 11, CHARIMA, SEDICOUP, OTIS, EFDCID, MIKE3, HEC-RAS, 3ST1D, SERATRA, SUTRENCH-2D, MOBED2, FLUVIAL 12, MIKE 21, DELFT 2D, ECOMSED, CH3D-SED, MIKE 3, DELFT 3D and TELEMAC (Papanicolaou et al., 2008). Water Erosion Prediction Project (WEPP) model is a process-based model based on infiltration theory, hydrology, soil physics, plant science, hydraulics and erosion mechanics (Pandey et al., 2009).The solution of the physically based model is either based on analytical or numerical approach.

Discrepancies between physically based sediment transport models and measurements are observed due to the oversimplification of the problem by using an inappropriate model, inappropriate input data, lack of appropriate data for model calibration, unfamiliarity with the limitations of the sediment transport equations and computational errors of numerical schemes. The applicability of these models to all rivers is limited due to the simplification of important parameters and boundary conditions considered (Nagy et al., 2002). Moreover, these models warrant huge amount of data and require substantial computational time to implement. Models such as black box models like Autoregressive (AR), Autoregressive Moving Average (ARMA) and Autoregressive Integrated Moving Average (ARIMA); and regression based models like Multiple Linear Regression (MLR) have been applied under limited data availability conditions. But the results obtained from these models are not always satisfactory. In recent years, the newer techniques such as Artificial Neural Networks (ANN) and Fuzzy logic are being explored and the proven better performance of these techniques over the conventional models has enabled the modelers to apply in many real world problems. The main advantage of the ANN models over traditional models is that they do not require information about the complex nature of the underlying process under consideration to be explicitly described in mathematical form.

Neural networks approach has been applied in many areas of water resources due to its capability in representing any nonlinear processes by given sufficient complexity of the trained networks (ASCE 2000a, 2000b; Govindaraju and Rao, 2000; Maier and Dandy, 2000). Many applications of ANN in modelling of sediment yield are reported in the literature (Nagy et al., 2002; Lohani et al., 2007; Jothiprakash and Garg, 2009). Selection of input to the ANN is based on the properties of flow and sediment such as tractive shear stress, velocity ratio, suspension parameter, longitudinal slope, water depth ratio, Froude number, Reynolds number, stream width ratio, depth scale ratio and mobility number. The ANN model for the simulation of sediment yield is developed with historical data of rainfall, sediment discharge and discharge of flow. The Multiple Linear Regression model (MLR) and other models such as AR, ARMA, ARIMA are also developed with same data.

MODELLING OF SEDIMENTATION PROCESS IN LAKE

The governing equations for the sedimentation process in the lake are **(1)** Continuity and momentum equations for sediment laden water **2)** The sediment continuity equation.

The continuity equation for sediment – laden water is

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}+\frac{\partial A_d}{\partial t}-q_l=0 \tag{3}$$

Where Q - Discharge of sediment-laden water

A - Cross sectional area of the lake

A_d -Volume of deposition or erosion of sediment on unit length of lake bed

q_l -Lateral inflow of sediment laden water into the lake

The momentum equation for sediment-laden water is

$$\frac{\partial(\rho\beta QV)}{\partial X}+\frac{\partial(\rho Q)}{\partial t}+qA\frac{\partial(\rho h)}{\partial x}=\rho gA(S_0-S_f)+\rho q_l v_l \tag{4}$$

Where V - Mean flow velocity

g - Gravitational acceleration

ρ - Density of the sediment -laden water

β - Momentum correction factor for velocity distribution

h - Flow depth

S_o - Bed slope

S_f - Friction slope

q_l - Lateral inflow of sediment-laden water into the lake

V_l - Velocity component of lateral blow

The sediment continuity equation is

$$\frac{\partial Q_s}{\partial x} + p\frac{\partial A_d}{\partial t} + \frac{\partial (A c_s)}{\partial t} - q_{sl} = 0 \quad (5)$$

Where Q_s - Total sediment load in units of volume per unit time

p - Volume of sediment in a unit volume of bed layer

C_s - Average sediment concentration inflow in the cores section on volume basis

q_{sl} - lateral sediment inflow in to the lake

Numerical Solutions

The available numerical methods of solution of governing equations can be classified as:

(a) Method of characteristics,
(b) Finite difference methods,
(c) Finite element methods.

Finite differences schemes

A function $f(x,t)$ with two independent variables *x* and *t* can be represented in *x-t* plane as given in Fig. 1 as finite difference grid. The grid interval for distance and time is given as Δx and Δt respectively. The values of unknown time level are computed from the known values of time level. The known conditions specified at time *t=0* are referred as *initial conditions*. The conditions specified at the channel ends are called as the *end* or *boundary conditions*. If the computations progress from one step to the next, then the procedure is referred to as a *marching procedure*. Most of the phenomena described by hyperbolic partial differential equations are solved by using marching procedures.

There are several possibilities for approximating the partial derivatives of the function $f(x,t)$ with respect to *x* and *t*. The spatial partial derivatives replaced in terms of the variables at the known time level referred to as the *explicit finite differences*, whereas those in terms of the variables at the unknown time level are called *implicit finite differences*. Some typical finite-difference approximations for the spatial partial derivative, $\frac{\partial f}{\partial x}$ at the grid point *(i, k)* for the known time level *k* and unknown time level *k+1* are given as follows:

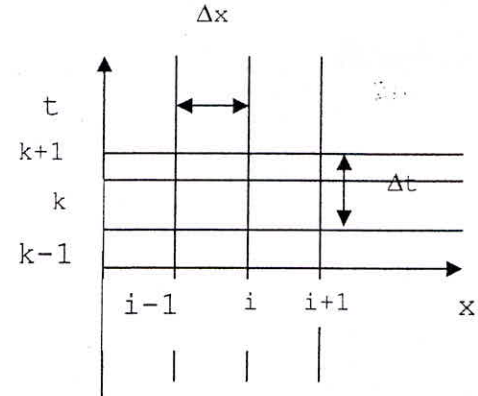

Fig. 1. Finite-difference grid

Explicit finite differences

Backward: $\frac{\partial f}{\partial x} = \frac{f_i^k - f_{i-1}^k}{\Delta x}$ Forward: $\frac{\partial f}{\partial x} = \frac{f_{i+1}^k - f_i^k}{\Delta x}$ (6)

Central: $\frac{\partial f}{\partial x} = \frac{f_{i+1}^k - f_{i-1}^k}{2\Delta x}$

Implicit finite differences

Backward: $\frac{\partial f}{\partial x} = \frac{f_i^{k+1} - f_{i-1}^{k+1}}{\Delta x}$ Forward: $\frac{\partial f}{\partial x} = \frac{f_{i+1}^{k+1} - f_i^{k+1}}{\Delta x}$ (7)

Central: $\frac{\partial f}{\partial x} = \frac{f_{i+1}^{k+1} - f_{i-1}^{k+1}}{2\Delta x}$

The above schemes are derived by simplifying by Taylor series expansion of the functions $f(x+\Delta x)$ and $f(x-\Delta x)$.

Preissmann Implicit Scheme

The Preissmann scheme has been extensively used since the early 1960's. It has the advantages that a variable spatial grid may be used; steep wave fronts may be properly simulated by varying the weighting coefficients; and the scheme yields an exact solution of the liberalized form of the governing equations for a particular value of Δx and Δt. The partial derivatives and other coefficients are approximated as follows:

$$\frac{\partial f}{\partial t} = \frac{\left(f_i^{k+1} + f_{i+1}^{k+1}\right) - \left(f_i^k + f_{i+1}^k\right)}{2\Delta t} \tag{8}$$

$$\frac{\partial f}{\partial x} = \frac{\theta\left(f_{i+1}^{k+1} - f_i^{k+1}\right)}{\Delta x} + \frac{(1-\theta)\left(f_{i+1}^k - f_i^k\right)}{\Delta x}$$

$$f = \frac{1}{2}\theta\left(f_{i+1}^{k+1} + f_{i}^{k+1}\right) + \frac{1}{2}(1-\theta)\left(f_{i+1}^{k} + f_{i}^{k}\right)$$

in which θ is a weighting coefficients; in the partial derivatives *f* refers to both *u* and *h*, and *f* as a coefficient stands for S_f and *u*. by selecting a suitable value for *θ*, the scheme may be totally explicit (*θ =0*) or implicit (*θ =1)*. The scheme is stable if $0.55 < \theta \leq 1$. Steep wave fronts are properly simulated for low values of θ, but there are oscillations behind the wave front. These oscillations are eliminated for *θ* close to unity; however, steep wave fronts are somewhat smeared. For typical applications, θ = 0.6-0.7 may be used. Substituting the above scheme approximations and the coefficients into Saint Venant equations (continuity and momentum equations) and simplifying, we get two simultaneous linear equations as follows;

$a\Delta u_{i+1} + b\Delta u_i + c\Delta h_{i+1} + d\Delta h_i + e = 0$ (Continuity equation)
(9)
$a'\Delta u_{i+1} + b'\Delta u_i + c'\Delta h_{i+1} + d'\Delta h_i + e' = 0$ (Momentum equation)

The above equations contain four unknowns $u_i^{k+1}, h_i^{k+1}, u_{i+1}^{k+1}, h_{i+1}^{k+1}$. *2N* equations are formed when the above two equations are written for each grid point. *N* is the number of reaches on the channel. The equations cannot be written for the grid points at the down stream end. However the total number of unknowns to be solved is *2(N+1)*. For unique solution, two more equations are required and those are given *end conditions*. The nonlinear terms are linearized by Taylor series and Power series.

Boundary conditions

The equations describing the boundary conditions such as rating curve, discharge equation are directly included in the system of equations.

Stability

The scheme is unconditionally stable provided $\theta > 0.5$ i.e., the flow variables are weighted toward the *k+1* time level. An unconditional stability means that there is no restriction on the size of *Δx* and *Δt* for stability. However for accuracy C_n (Courant number), should be close to 1.

Solution procedure

The equations when written for all grid points in the river reach constitute a very special system of linear equations because all elements in the corresponding matrix vanish except those in the five diagonals. For this system, the double sweep method of solution is very efficient and suitable for automatic computation. The computer programs for the standard numerical technique for solving system of 2N equations such as Gauss Elimination technique require storage of 2N × 2N matrix and the number of operations in the solution is proportional to N^3 whereas in the double sweep method, both the storage and the number of operations in the solutions are proportional to N.

Depth of sediment at a cross section

The ΔA_d, which is equal to $A^{n+1} - A^n$, is computed by discretizing the sediment continuity equation by explicit scheme once the depth and discharge of water at a particular section is determined by implicit scheme as explained above. The change in depth of the bed, Δz, is computed from $\Delta A_d / T$ where T is the top width of the cross section.

ANN MODEL FOR SEDIMENT YIELD

The ANN model for the simulation of sediment yield is normally developed using the antecedent rainfall, sediment yield and discharge values of upstream stations as input vector. Determining the number of antecedent rainfall, sediment yield and discharge values involves finding the lags of rainfall, sediment yield and discharge values that have significant influence on the predicted sediment yield. These influencing values corresponding to different lags can be very well established through statistical analysis of the data series (Sudheer al., 2002). The input vector is selected generally by trial and error method. The simple correlation between the dependent and independent variables helps in selecting the significant input vector to the model. To identify the input vector, detailed correlation analysis of rainfall, sediment yield and discharge values is to be done. Autocorrelation (ACF), partial autocorrelation function (PACF) and cross correlation function (CCF) of the input variables, can be used to select the significant input variables and thus the trial and error method of input selection can be avoided. Once the input vector is selected the ANN is trained and validated with the recorded data set. Now the ANN model is ready to predict the sediment yield with new input data for a specified period. The MLR model is also developed with the input vector selected by statistical analysis of the data.

REFERENCES

ASCE Task Committee on Application of Artificial Neural Networks in Hydrology. (2000a). "Artificial neural networks in hydrology-I: Preliminary concepts." J. Hydrol. Engrg., 5(2), 115-123.

ASCE Task Committee on Application of Artificial Neural Networks in Hydrology. (2000b). "Artificial neural networks in hydrology-II: Hydrologic applications." J. Hydrol. Engrg., 5(2), 124-137.

Enabnit, D., Guenther, G. and Rulon, T., (1979). "Airborne laser hydrography." Proc. Remote Sensing Symp., U.S. Army Corps of Engineers, Oct. 29-30, Reston, Va., USA. pp. 71-72.

Gao, P., and Pasternack, G. (2007). "Dynamics of suspended sediment transport at field-scale drain channels of irrigation-dominated watersheds in the Sonoran Desert, southeastern California." Hydrolog. Process., 21(16), 2081-2092.

Garde, R. J., and Rangaraju, K. G. (1985). Mechanics of sediment transportation and alluvial stream problems, Wiley Eastern Limited, New Delhi.

Govindaraju, R. S., and Rao, A. R. (2000). Artificial neural networks in hydrology, Kluwer Acdemic, Dordrecht, The Netherlands.

Guy, H.P., (1978). "Sediment" in National handbook of recommended methods for water data acquisition–Chapter 3, Office of Water Data Coordination, U.S. Geological Survey, Reston, Va, USA.

Jothiprakash, V., and Garg, V. (2009). "Reservoir Sedimentation Estimation using Artificial Neural Networks." J. Hydrol. Engrg., 14(9), 1035-1040.

Kusumgar, S., Agrawal, D.P., Bhandari, N., Despande R.D., Raina, R., Sharma, C., and Yadav, M.G. (1992). " Lake sediment from Kashmir Himalaya: Inverted 14C chronology and its implications." Radiocarbon 34 (3): 561-565.

Lohani, A. K., Goel, N. K., and Bhatia, K. K. S. (2007). "Deriving stage-discharge-sediment concentration relationships using Fuzzy logic." Hydrol. Sci. J., 52(4), 793-807.

Maier, H.R., and Dandy, G.C. (2000). "Neural networks for the prediction and forecasting of water resources variables: A review of modelling Issues and applications." Environmental Modelling & Software, 15, 101-124.

Nagy, H. M., Watanabe, K., and Hirano, M. (2002). "Prediction of sediment load concentration in rivers using artificial neural networks." J. Hydr. Engrg., 128(6), 588-595.

Neitsch, S. L., Arnold, J.G., Kiniry, J. R., and Williams J. R. (2005). Soil and Water Assessment Tool Theoretical Documentation – Version 2005, Grassland, Soil and Water Research Laboratory, Agricultural Research Service, 808 East Blackland Road, Temple, Texas 76502.

Pandey, A., Chowdhary, V. M., Mal, B. C., and Billib, M. (2009). "Application of the WEPP model for prioritization and evaluation of best management practices in an Indian watershed." Hydrolog. Process. 23(), 2997-3005.

Papanicolaou, A, N., Elahakeem, M., Krallis, G., Prakash, S., and Edinger, J. (2008). "Sediment transport modelling review-Current and Future developments." J. Hydr. Engrg., 134(1), 1-14.

Parajuli, P. B., Nelson, N. O., Frees, L. D., and Mankin, K. R. (2009). "Comparison of AnnAGNPS and SWAT model simulation results in USDA-CEAP agricultural watersheds in south-central Kansas." Hydrolog. Precess. 23(5), 748-763.

Pemberton, E.L., Blanton, J.O. (1980). "Procedures for monitoring reservoir sedimentation." Symposium on Surface Water Impoundments, Minneapolis, Minnesota, USA.

Shahin, M. M. A. (1993). "An overview of reservoir sedimentation in some African river basins." Sediment Problems: Strategies for Monitoring, Prediction and Control (Proceedings of the Yokohama Symposium, July 1993), IAHS Publ. No. 217, 93-100.

Sudheer, K. P., Gosain, A. K., and Ramasastri, K. S. (2002). "A data-driven algorithm for constructing artificial neural network rainfall-runoff models." Hydrolog. Process., 16(6), 1325-1330.

Tayfur, G. (2002). "Applicability of sediment transport capacity models for nonsteady state erosion from steep slopes." J. Hydrol. Engrg., 7(3), 252-259.

Vanoni, V.A., (1977). "Sediment engineering: Manual on Engineering Practice". American Society of Civil Engineers Manuals and Reports on Engineering Practice, No. 54, New York, 745 pp.

Wolf, P.R. (1974). Elements of Photogrametry. McGraw Hill Book Company Inc., New York, 562 pp.