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REVIEW ARTICLE

Soil erosion, sediment yield and sedimentation of reservoir: a review

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Abstract Sedimentation is an important parameter to assess the life of a reservoir. Seventy-eight years ago, Cook was the first to identify mathematically, the three major factors affecting soil erosion in the catchment of a reservoir. As sedimentation is dependent on sediment yield and sediment yield depends on soil erosion, it is required to predict all three parameters to estimate the life of a reservoir. Since then many researchers carried their research dealing with soil erosion, sediment yield and sedimentation in various reservoirs for its practical significance. The aim of this article is to present a comprehensive state-of-the-art review of the important investigations on soil erosion, sediment yield and sedimentation in various reservoirs highlighting the governing mathematical background of these problems. 198 references are included in this review paper.

List of symbols

C''	Constant
A	Soil loss per unit area in unit time ($ML^{-2}T^{-1}$)
S	Slope-steepness factor
L	Slope length factor
P	Support practice factor
R	Rainfall erosivity factor (MLT^{-4})
K	Soil erodibility factor ($L^{-3}T^3$)
C	Cover management factor
EI_{30}	Rainfall erosion index (MLT^{-3})
KE	Kinetic energy of the rainfall (MT^{-2})
I_{30}	Maximum 30 min intensity of the rainfall (LT^{-1})
I	Rainfall intensity (LT^{-1})
n	Total number of years over which data was collected
j	Number of year up to n
m	Total number of storms in a year
k	Number of individual storm up to m
e_r	Rainfall energy per unit depth of rainfall per unit area ($ML^{-1}T^{-2}$)
p_r	Depth of rainfall for the rth increment of a storm hyetograph which is divided into $\tilde{m}$ parts having constant rainfall intensity (L)
$\tilde{m}$	Division of storm hyetograph having constant rainfall intensity e_r
i_r	Constant intensity over the time increment (LT^{-1})
t_r	Length of time of the rth increment (T)
F	Modified Fournier index (L)
p_i	Mean rainfall for month i (L)
$\bar{P}$	Mean annual rainfall depth (L)
d_g	Geometric mean particle size (L)
f_i	Mass fraction of ith particle
d_i	Maximum diameter of particle (L)
d_{i-1}	Minimum diameter of particle (L)
LS	Topographic factor
λ	Field slope length (L)
k'	Exponent factor value
θ	Angle of slope
m'' and n''	Fitted regression coefficient
A_{crop}	Soil loss from cropped land area ($ML^{-2}T^{-1}$)

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A_{fallow}	Soil loss from fallow land area ($ML^{-2}T^{-1}$)
$NDVI$	Normalized difference vegetation index
L_{TM}	Landsat ETM
α, β	Two dimensionless parameters
Y	Sediment yield in a given day (M)
Q	Annual runoff volume (L^3)
$q_{p'}$	Peak rate of runoff volume (L^3T^{-1})
Q_{SV}	Volume of sediment yield per year (L^3T^{-1})
A_{catch}	Catchment area (L^2)
Q_s	Annual sediment yield rate (MT^{-1})
Q'	Mean annual sediment yield (L^3)
D_d	Drainage density (L^{-1})
FA	Arable land in the catchment (L^2)
FG	Grass land in the catchment (L^2)
FF	Forest land in the catchment (L^2)
FW	Waste land in the catchment (L^2)
$V_{S(p+1)}$	Total sediment volume of a reservoir at the water level $h_{(p+1)}$ (L^3)
$v_{S(q+1)}$	Change in storage of a reservoir in between two water levels (L^3)
p	0, 1, 2, 3, …
q	0, 1, 2, 3, …, p
Δh	Difference between two consecutive water levels of a reservoir (L)
$A_{res(p)}$ and $A_{res(p+1)}$	Corresponding water surface area of h_p and $h_{(p+1)}$ (L^2)
V_S	Total sediment volume (L^3)
$A_{res(0)}$	Original reservoir surface area at depth h_0 (L^2)
H	Maximum depth of reservoir (L)
h_0	Sediment depth at dam's wall position (new zero depth of the reservoir) (L)
V_0	Original reservoir capacity at depth h_0 (L^3)
A_{res}	Reservoir surface area at any depth h (L^2)
dh	Incremental depth (L)
$a_{p'}$	Relative area
$\bar{h}$	Relative depth
k'	Constant of proportionality
C', m', n'	Coefficients

p	Peak value
SV	Sediment volume
$Catch$	Catchment
s	Sediment
d	Density
$S(p + 1)$	Sediment at ($p + 1$) increment
$res(p)$	Reservoir at increment p
$res(p + 1)$	Reservoir at increment ($p + 1$)
0	Original
p'	Relative

Subscripts

30	30 min
i	Increment
r	Rainfall
g	Geometry
$Crop$	Cropped land
$Fallow$	Fallow land
TM	Thematic mapper
3, 4	Landsat band 3 & 4

Introduction

In reservoir, sedimentation is a phenomenon due to which the sediment particles get deposited in the form of bed load and suspended load after separating from their origin. In fluvial hydraulics, sedimentation is an important parameter as it provides a probability of being used as a capacity predicting device in all storage zones due to which life of a reservoir can be predicted; as there is a unique relationship between capacity and life of a reservoir. To be more explicit, for a given reservoir, sedimentation is dependent on sediment yield, which is defined as the sediment discharge through a river outlet per unit catchment area per unit time (ASCE 1982). Soil erosion in the catchment is also an important parameter as the sediment yield depends on it. In order to reduce the problem corresponding with the amount of sediment particles that ultimately deposit into the reservoir after getting eroded from the catchment, attempts have been made to relate the soil erosion, sediment yield and sedimentation into the reservoir, since these three parameters deal with the life of a reservoir directly or indirectly.

The objective of this paper is to present and analyze chronological review of soil erosion, sediment yield and sedimentation of reservoir to predict the life of reservoir, highlighting the governing equations for assessment of above three parameters. Researchers can do their advanced research, using the references included in the paper for their detailed investigations.

Background of soil erosion, sediment yield and sedimentation

The erosive effect of rainfall and runoff break away the sediment particles from the catchment of the reservoir (Hudson 1975) due to intense shear stress generated by the interaction of kinetic energy of raindrop and soil surface. This phenomenon has also been explained by Wischmeir (1960). According to Roose (1980), rainfall dominates over

the surface runoff in West Africa (256 times). Eroded sediment particles collide and break into smaller fragments. Transportation of sediment particles in a river begins when the induced shear stress by the flow overcomes the critical shear stress of the bed particles. Particles are in suspended form when the materials made up of very fine particles such as clay and silt are lifted as a result of turbulence and transported by the river. Bed load particles such as boulders are rolled and pushed along the river bed by the force of the river. When a reservoir loses its energy due to the reduction of rainfall, increasing evaporation and reduction of velocity, the sediment particles get deposited gradually in the reservoir due to gravity and consolidate over time. All the eroded sediment particles produced due to erosion in a watershed is transported out of it as there will be considerable temporary depositions in various phases and locations. However, there exists a relationship between the soil erosion and the sediment yield, which is represented using sediment delivery ratio (SDR = sediment yield at the catchment outlet/gross erosion in the catchment). Therefore, the sedimentation being a function of both soil erosion and sediment yield is used to determine the life of a reservoir.

Problem formulations

Predicting soil erosion

At a global scale, water erosion, is the main cause off soil degradation (Deniz et al. 2008) and about 80 % of the world's agricultural land suffers from moderate to severe erosion (Ritchie et al. 2003). Prediction of erosion is the most important in soil and water conservation practices in the catchment of a reservoir. In India, soil erosion is occurring at a rate of approximately 0.16 tones km^{-1} $year^{-1}$, of which about 10 % is deposited in reservoirs and 29 % is transported to the sea (Kirurhika et al. 2011). Cook (1936) identified three major variables for soil erosion and they are sensitivity of soil to erosion, potential erosivity of rainfall and runoff and soil protection afforded by plant cover. Zingg (1940) was the first to introduce mathematical equation to estimate the soil erosion losses as a function of slope steepness factor (S) and slope length factor (L) in the following form:

$$A = C'' S^{1.4} L^{0.6} \tag{1}$$

where $C'' =$ constant. Later, Smith (1941) modified the Eq. (1) by introducing a conservation factor P.

$$A = C'' S^{1.4} L^{0.6} P \tag{2}$$

Browning et al. (1948) further modified Eq. (2) by adding soil erodibility and management factors. Wischmeier and Smith (1978) developed the universal soil loss

equation (USLE) for estimating soil erosion caused by the sheet and rill erosion under specified conditions. The soil loss per unit area in unit time, A is expressed as

$$A = RKLSCP \tag{3}$$

where $R =$ rainfall erosivity factor, $K =$ soil erodibility factor, $C =$ cover management factor. All the factors described in USLE are independent of each other. Primarily, USLE (index based, empirically derived model) predicts the average annual soil loss due to erosion by water for a long term, based on rainfall pattern, soil type, topography, crop system and management practices. USLE is the most widely used equation in erosion modelling (Fistikogli and Harmancioglu 2002). However, huge limitations are there to use USLE; such as in its original form it does not predict erosion in a spatial context; however this limitation is overcome when integrated with GIS. It also requires large amount of assets and time to prepare the input parameters to run the model in a new environment. Moreover, it cannot identify the events which cause large scale soil erosion as it is not event based. It also does not estimate wind, mass, tillage, channel or gully erosion as it is developed to simulate sheet and rill erosion only. To overcome these drawbacks, Renard et al. (1996) developed revised universal soil loss equation (RUSLE) and Kinnell and Risse (1998) developed a new version of universal soil loss equation (USLE-M) to predict the soil loss by modifying the soil loss erosion factors. Later, RUSLE 1.06c (USDA-ARS-NSL 2003), which is land-use independent and RUSLE 2 (USDA-ARS-NSL 2003) are developed based on USLE including additional features that further analyze particular aspects of the soil erosion process. Foster (2006) compared the above three models (USLE, RUSLE 1.06c, RUSLE 2) to find their efficiencies to determine the soil loss. According to their findings, USLE does not compute deposition whereas RUSLE 1.06c computes deposition as a function of soil texture. Moreover, RUSLE 2 computes how deposition changes sediment characteristics along the slope, which in turn affects computed deposition. They concluded that RUSLE 2 is more powerful and easy-to-use erosion prediction model than the other two models especially for rill and inter-rill erosion. It also presents the spatial heterogeneity of soil erosion that is too feasible with reasonable costs and better accuracy in larger areas (Angima et al. 2003). However, the drawbacks of these models are that they are not capable of calculating runoff and account for the process of sediment transport.

Rainfall erosivity factor

Wischmeier and Smith (1978) found that the energy available to erode the sediment particles from its origin during the

rainfall is the product of kinetic energy contained within the rainfall and the intensity of the rainfall. It was found that maximum 30 min intensity of rainfall yields the best results. Hence, the rainfall erosion index (EI_{30}) is defined as

$$EI_{30} = \frac{KE \times I_{30}}{100} \tag{4}$$

where KE = kinetic energy of the rainfall, I_{30} = maximum 30 min intensity of the rainfall. KE is expressed as follows:

$$KE = 210.3 + 89 \log I \tag{5}$$

where I = rainfall intensity. The rainfall erosivity factor is defined as the summation of each rainfall erosion index within a given period in the studied area and is expressed as

$$R = \frac{1}{n} \sum_{j=1}^{n} \left[\sum_{k=1}^{m} (KE)(I_{30})_k \right]_j \tag{6}$$

where k = number of individual storm up to m, m = total number of storms in a year, j = number of year up to n and n = total number of years over which data was collected. According to Renard et al. (1996), kinetic energy is calculated as

$$KE = \sum_{k=1}^{\tilde{m}} e_r p_r \tag{7}$$

where e_r = rainfall energy per unit depth of rainfall per unit area, p_r = depth of rainfall for the rth increment of a storm hyetograph which is divided into $\tilde{m}$ parts having constant rainfall intensity e_r, is determined using the following equation:

$$e_r = 1099 \left(1 - 0.072^{(-1.27 i_r)} \right) \tag{8}$$

where i_r = constant intensity over the time increment.

$$p_r = i_r t_r \tag{9}$$

where t_r = time of the rth increment. Renard and Freimund (1994) proposed an equation to correlate the mean annual rainfall depth $\bar{P}$ with the modified Fourier index F, introduced by Arnoldus (1980) which is defined as

$$F = \sum_{i=1}^{12} \frac{p_i^2}{\bar{P}} \tag{10}$$

where p_i is the mean rainfall for month i. It also considers the effect of seasonal variation of rainfall. When there is lack of daily rainfall data, F index based on mean annual precipitation is used as a parameter to measure R to which it is linearly correlated. Later, different experiments (Ferro et al. (1991, 1999); Aronica and Ferro 1997) were conducted to modify F index and to correlate it with R. In addition, research works have been carried out to determine the effect of rainfall factor in the estimation of soil erosion

by suggesting different climatic erosivity indexes (Wischmeier index 1959). Also, empirical equations of soil erosivity factor R as a function of mean annual precipitation $\bar{P}$ discussed in the succeeding sections were reported by Mikhailova et al. (1997) and Torri et al. (2006). In Australia and United States, Yu and Rosewell (1996) and Renard and Freimund (1994) respectively, reported a good correlation between annual rainfall and R. Yu et al. (2001) concluded that the rainfall erosivity factor reflects the effect of climatic change on the soil erosion phenomenon. Yu (1999) compared the R factor in USLE and RUSLE and concluded that the calculated R-factor using the unit energy equation is greater than that for RUSLE and the difference increases as peak rainfall tends to decrease.

To calculate R factor, series of more than 20 years of rain gauge data are recommended, but this length of time series is not found in many parts of the world (Capolongo et al. 2008; Hoyos 2005; Lee and Heo 2011). Also the high-resolution rainfall data needed to directly compute the rainfall erosivity are not available for many locations. Hence, simplified methods for predicting rainfall erosivity in many countries are using readily available data. Moreover, calculations of such data are intricate and time consuming. Several researchers found that high value of annual precipitation does not necessarily produce higher values of erosivity because of variation in rainfall intensity. Panagos et al. (2015) published a map of rainfall erosivity for Europe in which maximum half hourly intensity instead of I_{max30} was used. Auerswald et al. (2015) studied the deficiencies of the map produced by Panagos et al. (2015) and reported that the values of this map contain some bias. The temporal resolution of the rainfall data was insufficient, which likely underestimates rainfall erosivity by about 20 %. Different time periods had not been taken into account which can modify rainfall erosivity by more than 50 %. Also use of precipitation data instead of rainfall data causes the overestimation of rainfall erosivity in areas with significant snowfall. Moreover, the seasonal variation of rainfall erosivity is not considered, which restricts using of the erosivity map for erosion prediction in many cases. Maetens et al. (2012) conducted studies in Europe and Mediterranean by reviewing data from 227 stations and 1056 soil erosion plots to predict the effect of land use on annual soil erosion, annual runoff and annual runoff coefficient. They concluded that the soil loss does not correlate better with erosivity indices than with total rainfall. In addition, some discussions on prediction of R are also available elsewhere (Lee and Heo 2011; Oliveira et al. 2013b).

Soil erodibility factor

The soil erodibility factor K is affected by intrinsic soil properties. The main soil properties affecting K are soil

texture, organic matter, structure and permeability of the soil profile. K shows to what extent soil can be detached by rainfall splash and surface flow (Zhang et al. 2008). It depends on the local soil properties including physical, chemical, biological and mineralogical and can be determined through sample analysis of the soil or from a soil map or pedological survey of the site or through a combination of these. In RUSLE, all properties are categorized into two groups: properties that impact rate of infiltration, mobility of water through soil and water storage capacity; and properties that influence dispersion, detachability, abrasion and movement of soil particles due to rainfall and runoff (Wischmeier and Mannering 1969; SWCS 1995; Soil Survey Staff 1997). K may have temporal as well as spatial variation for a particular type of soil. According to Wischmeier and Smith (1978), K factor (crop management factor) may be calculated for the unit plot (standard plot for which $LS = 1$ and $CP = 1$) by the following equation:

$$K = \frac{A}{R} \tag{11}$$

Renard et al. (1996) proposed a formula to determine the K factor on the basis of global data of measured K values, obtained from 225 soil classes.

$$K = 0.0034 + 0.0405 \times \exp\left[-0.5\left(\frac{\log d_g + 1.659}{0.7101}\right)^2\right] \tag{12}$$

where

$$d_g = \exp\left(\sum f_i \ln\left(\frac{d_i + d_{i-1}}{2}\right)\right) \tag{13}$$

where d_g is the geometric mean particle size, d_i is the maximum diameter, d_{i-1} is the minimum diameter and f_i is the corresponding mass fraction. K may be accurately estimated from soil loss data spread over the prolonged period, though it is very expensive, time consuming and impractical for many situations (Renard et al. 1997). Geostatistical methods like sequential Gaussian can be used to simulate K from the soil of the study area, which minimizes risk and takes proper land management practices with useful information (Wang et al. 2001). Breshears et al. (2003) commented that there are several methods of estimating K such as measuring soil physiochemical properties, scouring, rainfall simulation, plot experiment etc. Some researchers (Zhang et al. 2007) pointed out that soil erodibility may be influenced by the presence of lime. Lime content increases aggregate stability, resulting in a decreased K (Zhang et al. 2008). Vaezi et al. (2008) directly related the lime content to K. At present, long term monitoring of soil loss from natural runoff plots is the best method to estimate K for a given soil (Kim et al. 2005).

However, some important discussions on K factor of RUSLE are also available elsewhere (Breshears et al. 2003; Kim et al. 2005; Zhang et al. 2008; Vaezi et al. 2008).

Topographic factor

The effect of topography of land on soil erosion can be reflected by L and S factor in USLE. Due to the difficulty in the calculation of LS factor, an average LS value is assumed for entire region. This factor can be calculated in various ways depending on unit preferences and available data. According to Risse et al. (1993), Hann et al. (1994) and Biesemans et al. (2000), the overall efficiency of USLE model depends mainly on the topographic factor (LS) and the crop management factor C.

Different empirical relations are used to determine this factor. Combining all the findings by the researchers (Zingg 1940; Smith and Whitt 1948), the following expression represents the relation of LS factor with soil erosion

$$LS = \left(\frac{\lambda}{22.13}\right)^{m''}\left(\frac{\sin \theta}{\sin 5.143°}\right)^{n''} \tag{14}$$

where m'' and $n'' = $ fitted regression coefficients. According to Wischmeier and Smith (1978), the product of L and S is given by the following equation:

$$LS = \left(\frac{\lambda}{22.13}\right)^{k'}\left[65.41 \sin^2 \theta + 0.065\right] \tag{15}$$

where $\lambda = $ field slope length, $k' = $ exponent factor ranging from 0.2 to 0.5 and $\theta = $ angle of slope.

It was concluded from the findings of that increase in slope length and slope steepness cause higher velocities in overland flow and correspondingly higher erosion. Liu et al. (1994) stated that various functional forms (linear, power or polynomial forms) of soil loss predictive equations produce identical values of soil loss caused on hillsides by rainfall and runoff for slope up to 25 %. However, they provide different values of soil loss beyond this slope gradient. Some studies have concluded that slope steepness rather than slope length affects the value of the topography factor (McCool et al. 1987; Van et al. 2004). Computing of length slope gradient factor (LS factor) of USLE/RUSLE equation is very difficult. According to Mitasova et al. (1996), this drawback can be minimized by modifying LS factor where the influence of profile convexity/concavity using segmentation of irregular slopes is incorporated. Oliveira et al. (2013a, b) gave an idea to use Shuttle Radar Topography Mission (SRTM) data for computing RUSLE topographic factor in absence of topographic information. Though the effect of slope is considered in USLE, study can be conducted to examine the effect of slope on the determination of USLE-K factor.

Crop management factor

C factor (crop management factor) is the ratio of soil loss from cropped land under specified conditions (A_{crop}) to the corresponding clean-tilled continuous fallow (A_{fallow}). It is influenced by various factors like specific vegetation cover, rotation sequence, overall functions of managing measures and the distribution of erosive precipitation in different vegetative period of crop. It is expressed as

$$C = \frac{A_{crop}}{A_{fallow}} \times 100\ \%.$$ (16)

In USLE, the crop management factor is derived based on empirical equations with measurements of ground cover, aerial cover and minimum drip height whereas in the RUSLE, the effect of crop and management is analyzed in more detail as the *C* factor is composed of subfactors such as impact of previous cropping and management, the protection of soil surface by vegetative canopy, reduction in erosion due to surface cover and surface roughness. For specific crop rotations, the approach to measure *C* value by field experiments is very time-consuming.

Takken et al. (1999) concluded that the relationships between vegetation and erosion could be further improved considering the distribution of vegetation. Important discussions on factor *C* are also available in different places (Cai et al. 2000; Donald et al. 2003). Constant values of the RUSLE *C* factor, produced in earlier studies, are usually used to evaluate soil erosion in watersheds. These values, however, do not accurately represent vegetation variation, particularly in large areas, which can result in mistaken estimates of soil loss. To avoid this problem many studies have been conducted to determine *C* factor by using satellite images for which various sub factors such as land cover classification map, image bands, ratios of image bands, vegetation index and vegetation coverage are needed to process using remote sensing techniques (Manoj and Umesh 2000; Wang et al. 2002; Vrieling 2006). Large effort has been made on calculating and mapping the *C* factors for use in soil erosion modelling by means of Geographic Information System, remote sensing data and spectral indices (de Asis and Omasa 2007; Wang et al. 2002). The normalized differenced vegetation index (NDVI) derived from multispectral images is currently one of the most common environmental covariates of vegetation in order to monitor and analyze vegetation, its properties, and spatial and temporal changes (Wang et al. 2002; Lin et al. 2002). As a function of the NDVI, the fractional vegetation cover (FVC) provides information on the percentage of vegetation cover. The NDVI is an indicator of vegetation growth, for which Landsat-ETM (L_{TM}) is given by the following equation:

$$NDVI = \frac{L_{TM4} - L_{TM3}}{L_{TM4} + L_{TM3}}$$ (17)

The value of NDVI ranges between −1.0 to +1.0. According to Van Leeuwen and Sammons (2004), the following formula is used to generate *C* factor

$$C = e^{(\alpha((NDVI)/(\beta - NDVI)))}$$ (18)

where α and β are two dimensionless parameters that determine the shape of the curve relating NDVI and the *C* factor. Van der Knijff et al. (1999, 2000) found that the values of 2 and 1 selected for the parameters α and β produces good result for the value of crop management factor. These methods employ regression model to make correlation analysis between *C* factor values measured in field or obtained from guide tables and NDVI values derived from remotely sensed images. The goal of regression analysis is to estimate the unknown values of dependent variable based upon values of an independent variable using a mathematical model. However, under tropical climate conditions, the *C* factor tends to be higher than that calculated by these methods for the same vegetation cover. Therefore, a new method considering the variation of climatic conditions for calculating the RUSLE *C* factor, based on NDVI rescaling, was proposed by Durigon et al. (2014). Very few research works were conducted on the crop rotational scheme. So investigations should be carried out considering the crop rotational scheme and positioning of crops in their rotation to assess the variation of the *C*-factor values.

Practice factor

P-factor represents the effect of surface conditions like contouring, strip cropping and terraces on flow paths and hydraulics. This variable is set equal to 1 in military land management applications. However, different *P* factor scenarios may be considered to determine the various effects of different management techniques on soil-loss estimates. The documentations of softwares like FLU-VIAL-12 (Chang 2006) and SWAT (Neitsch et al. 2005) describe the modelling approaches for the prediction of USLE factors.

The evaluation of each subfactor of USLE or RUSLE is difficult because of many possible combinations, and the time spent with data acquisition and analysis. However, the advantage of predicting soil loss by using either of these methods is that over long period of time and large area, overestimations and underestimations can compensate each other, resulting in a good overall assessment of total soil loss. Schonbrodt et al. (2010) and Gabriels et al. (2003) discussed different issues and problems associated with USLE/RUSLE. Among the different techniques to predict

USLE, confusions are there regarding the methodology to be used for the prediction of different factors. It depends on the site condition and availability of data. However, all the values can't be validated due to the lack of field data. Therefore, detailed field surveys are necessary for the development of different USLE factors.

Models for predicting soil erosion

Models of estimating the soil erosion can be classified into three categories: empirical models, physical models and conceptual models. Empirical models are developed from the statistical analysis on the information obtained from experimental measurement or field measurement, specially used for identifying the sources of sediments (Merritt et al. 2003). Therefore, empirical models are used widely in catchment scale as they are applied uniformly over the region. However, they are unable to analyse the dynamics of sediment erosion and deposition in the watershed as it contains less amount of input data.

Physically-based models are developed based on the conservation of law of mass and energy to derive partial differential equations for describing runoff and sediment yield induced by independent rainfall events in the watershed (Bennett 1974). They are mostly used to describe the effect of land surface characteristics such as topography, slope, vegetation, soil, as well as climate parameters including precipitation, temperature and evaporation (Legesse et al. 2003). But the disadvantage of this type of model is the requirement of large amount of data.

Conceptual models, which are mixture of empirical and physically-based models, provide an indication of qualitative as well as quantitative processes within a catchment without considering process interactions. Table 1 represents a brief description of empirical, physical and conceptual models for predicting soil erosion.

Various empirical equations of soil loss due to erosion were reported by the researchers (Van Doren and Bartelli 1956; Adinarayana et al. 1999 and Veihe et al. 2001). Lu et al. (2004) concluded that the methods based on erosion plots have drawbacks in respect of cost, representativeness and reliability of the resulting data. Hence, these methods cannot provide spatial distribution of soil erosion loss in complex environments. Presently, the hydrological models are being used incorporating the topographical features of terrain, land use and soil characteristics from remote sensing satellites and GIS (Star et al. 1997). Investigators (Mitasova et al. 1996; Yitayew et al. 1999; Millward and Mersey 1999; Fernandez et al. 2003; Lim et al. 2005; Bayramin et al. 2008) combined the USLE/RUSLE with GIS to estimate the magnitude and spatial distribution of soil erosion. The combined use of GIS with erosion models has been proved to be an effective approach for estimating the magnitude and spatial distribution of soil loss. Manual calculation allows the determination of soil loss only from the land as a whole. Therefore, the calculation of subfactors in GIS environment gives the possibility of determining the total soil loss from the whole plot, as well as from each network element. Moreover, this approach helps to implement erosion control measures only in those parts of the land that are truly at risk. However, important discussions on the evaluation of subfactors of USLE/RUSLE by using GIS, are also available elsewhere (Fernandez et al. 2003; Fu et al. 2006; Lim et al. 2005).

Jetten et al. (1999) conducted their studies by combining a raster-based approach to spatial distribution, with a fully dynamic approach to predict time-variable hydrographs. They concluded that every soil erosion model has limitations in terms of its representation of erosion processes. One source of the positional error might lie with flow path delineation while another source of uncertainty is the high spatial variability of parameters which are assumed constant by the model. Baskan et al. (2010) carried out investigations to assess the application of the sequential Gaussian simulation (SGS) for mapping of soil erodibility factor of the USLE/RUSLE methodology coupled with spatial uncertainty. Due to the absence of sediment data over a period of time, ^{137}Cs (Cesium) technique can be used to quantify the soil erosion very quickly and accurately. Using this technique, large number of experiments have been conducted in different regions for predicting soil erosion (Kosmas et al. 2001; Li and Poesen 2003; Fukuyama et al. 2005; Yang et al. 2006; Zhang et al. 2006, 2008).

Predicting sediment yield

Sediment yield from a storm

The determination of SDR is necessary to predict sediment yield at the outlet of catchment. Walling (1983) and Kinnell (2004) discussed the limitations of using SDR to determine sediment yield. Certain other empirical equations to predict SDR discussed in the succeeding sections, were reported (Horowitz 2003; Schmidt and Morche 2006). In most of the applications, where SDR has been used to determine sediment yield, it is assumed that the value of SDR is constant whereas in practices they have been shown to vary for different storm events. SDR also possesses high level of uncertainty since it is a complex function of space and time.

Pacific Southwest Inter-Agency Committee first developed the semi-quantitative model (PSIAC) in 1968 to predict the sediment yield. The methodology works well even with less amount of data and includes the effect of gully erosion and topography. However, this semi-

Table 1 Different models for predicting soil erosion (Merritt et al. 2003)

Empirical Models	Physically Based Models	Conceptual Models
Musgrave equation	ANSWERS	Sediment concentration graph (Johnson 1943)
(Musgrave 1947)	(Beasley et al. 1980)	Renard-Laursenn Model
PSIAC Method	CREAMS	(Renard and Laursen 1975)
(Pacific Southwest Interagency Committee 1968)	(Knisel 1980)	Unit Sediment Graph
USLE	GUESS	(Rendon-Herrero 1978)
(Wischmeier and Smith 1978)	(Rose et al. 1983)	Instantaneous Unit Sediment Graph
SLEMSA	EPIC	(Williams 1978)
(Elwell 1978)	(Williams et al. 1984)	AGNPS
SEAGIS	TOPOG	(Young et al. 1989)
(DHI 1999)	(O'Loughlin 1986)	EMSS
RUSLE	WEPP	(Vertessey et al. 2001)
(Renard et al. 1996)	(Nearing et al. 1989)	HSPF
SEDNET	KINEROS	(Johanson et al. 1980)
(Prosser et al. 2001c)	(Woolhiser et al. 1990)	IQQM
RUSLE2	GUEST	(DLWC 1995)
(Foster et al. 2002)	(Misra and Rose 1990)	LASCAM
PESERA	dUSLE	(Viney and Sivapalan 1999)
(Kirkby et al. 2004)	(Flacke et al. 1990)	SWRRB
	EROSION2D	(USEPA 1994)
	(Schmidt 1991)	
	PERFECT	
	(Littleboy et al. 1992)	
	LISEM	
	(De Roo et al. 1994)	
	KINEROS2	
	(Smith et al. 1995)	
	EUROSEM	
	(Morgan et al. 1998)	
	WATEM/SEDEM	
	(Takken et al. 1999; Feng et al. 2010)	
	MIKE-11	
	(Hanley et al. 1998)	

quantitative approach is applied only in the planning purposes of dam construction and also for the analysis of the effect of the hydraulic structures on downstream sediment budgets.

Williams (1975) developed the USLE (Eq. 1) by replacing the rainfall energy with runoff which is expressed in the following form:

$$Y = 11.8 \left(Q \times q_{\bar{p}} \right)^{0.56} K(LS)CP \qquad (19)$$

where Y = sediment yield from an individual storm in a given day and $q_{\bar{p}}$ = peak rate of runoff volume. It was concluded that MUSLE eliminates the need of SDR and it may be used for individual storm event. Many researchers used MUSLE model to estimate sediment yield (Williams

and Berndt 1977; Arekhi and Rostamizad 2011) in different parts of the world along with different revisions.

Sediment yield from watershed

The most widely used common procedures to predict the sediment yield from a watershed are to use simultaneously flow duration curve as well as sediment rating curve (Crawford 1991), reservoir sedimentation survey data (Verstraeten and Poesen 2000) and estimation of soil erosion and sediment delivery ratio. Different empirical equations are there to calculate the sediment yield at the outlet of a reservoir. Khosla (1953) developed the equation to predict the volume of sediment yield in the following form:

$$Q_{SV} = 0.00323 A_{catch}^{0.72} \qquad (20)$$

where Q_{SV} = volume of sediment yield per year and A_{catch} = catchment area. But the drawback is that the equation underestimates the rate of sedimentation. Flaxman (1972) developed a more complicated empirical model that relates sediment yield to mean annual climate, watershed slope and soil characteristics. Later Dhruvnarayana and Ram (1983) developed the sediment yield equation in the following form:

$$Q_S = 5.5 + 11.1Q \qquad (21)$$

where Q_s = annual sediment yield rate and Q = annual runoff volume. Garde and Kothyari (1987) estimated the mean annual sediment yield (Q') from the large catchment and proposed the equation in the following form:

$$Q' = 1.182 \times 10^{-6} \times \bar{P}^{1.29} \times A_{catch}^{1.03} \times D_d^{0.40} \times S^{0.08} \times C^{2.42} \qquad (22)$$

where D_d = drainage density and

$$C = \left(\frac{0.8FA + 0.6FG + 0.3FF + 0.1FW}{A_{catch}} \right) \qquad (23)$$

FA denotes the arable land in the catchment and FG is the grass land, FF is the forest land and FW is the waste Land.

FAO (1997) performed traditional catchment experiments to measure the sediment yield at the outlet of a catchment and to assess the impact of changing land management practices on this yield. However, the traditional models are unable to predict the sediment yield accurately due to their inabilities to simulate accurately runoff rates and amounts, i.e. the hydrologic response at the basin scale. Suresh (2000) identified the factors which affect the sediment yield as land use, soil type, catchment size, climate and rainfall. Later Krishnaswamy et al. (2001) and Renschler and Harbor (2002) determined correlation between sediment yield and watershed area. Moreover, Sun et al. (2002), Paringit and Nadaoka (2003), Jain et al. (2005) combined geographic information system with the rainfall-runoff model, the soil erosion model and the sediment transport model to compute the runoff and sediment yield in the watershed and made it easy to utilize the huge amount of geographic and hydrological parameters simultaneously in a watershed. Dendy and Bolton (1976) concluded from the empirical studies that sediment yield decreases substantially as watershed area increases whereas Shen and Julien (1993) confirmed the conclusions made from the above intuition that the SDR may reach 10 % as watershed area reaches 100 km². However, this relation has some constraints as it encompasses huge amount of variables and has a limited theoretical basis. de Vente et al. (2007) reported that the sediment yield increases and decreases as a function of watershed area. The non linear relationship exists between them due to the spatial variation of topography, land use land cover or climate. The inverse relationship of SDR to watershed size has been assigned to longer travel distances (Parsons et al. 2006), longer travel times (Williams 1975) and lower average land slopes (Boyce 1975). Verstraeten and Poesen (2001) suggested that it might be more reliable to use sediment volume than sediment mass for sediment yield assessments. However, the use of reservoir sedimentation as a predicting tool of sediment yield accounts for some drawbacks such as the total deposition volume does not give information about temporal variation of sediment production and the calculated sediment yield is averaged over an extended time (Alatorre et al. 2012). Table 2 represents the empirical, physical and numerical models for predicting sediment yield. Numerical models do water routing on the basis of equal surfaces whereas physical based models do it on the basis of equal volumes for reservoirs with two outlet structures such as weir and orifice. In comparison to empirical and physical models, numerical models provide good prediction of shape and magnitude of the effluent sediment concentration graph. Verstraeten and Poesen (2002) carried out their studies to find the possibilities and limitations of the use of sedimentary deposits for determining the sediment yield in small water bodies. It was reported that the sediment depositions need to be converted to the sediment masses using the dry sediment bulk density. The measured sediment masses need to be corrected for assessing the trap efficiency of the small retention ponds to minimize the error to predict the sediment yield. The drawback of this method is that it is inadequate due to unavailability of data and it is incorporated with bedload transport which is very difficult to measure through sampling.

Laronne and Mosley (1982) presented a review on erosion and sediment yield whereas Araujo and Knight

Table 2 Different models for predicting sediment yield

Physically based models	Numerical models
DEPOSITS	STEP
(Ward et al. 1977)	(Verstraeten and Poesen 2001)
CSTRS	
(Wilson and Barfield 1984)	
BASIN	
(Wilson and Barfield 1985)	
1986 EPA Urban Methodology	
(Driscoll 1986)	
SHETRAN	
(Ewen et al. 2000)	

(2005) reviewed sediment yield measurement in different scales and concluded that the approaches for sediment yield measurement bear a much closer relationship to the temporal than to the spatial resolution.

Predicting sedimentation

Due to construction of dam, the transported sediments get deposited into the reservoir, causing reduction of the storage capacity. Analysis of sediment distribution is important to tackle the problems such as rising of bed level, increasing flood levels and entry of sediments into the reservoir. The sediment deposition can be determined directly based on either the analysis of the samples taken from geological drilling in the reservoir (Lee 1997) or in situ cross-section elevation measurements. But the disadvantages of these two methods are expensive and time consuming. Heinemann (1981), Graf (1984), Morris and Fan (1998) and Subramanya (2008) discussed the sedimentation phenomenon in the proper section of their books. Also, due to its practical importance, the Indian Standard (1994) recommended the estimation of sedimentation in reservoir at different elevations by the area increment and area reduction method.

Trap efficiency

Brown (1943) was the first to recognize the important feature of sedimentation into the reservoir, proposing a term trap-efficiency. The trap-efficiency is defined as the percentage of incoming sediments that is retained into the reservoir. It is simple to use, specially when the runoff data are missing. A curve was developed to correlate trap-efficiency with capacity- watershed area ratio. Churchill (1948) established a relationship between trap-efficiency and reservoir sedimentation index which is defined as residence time divided by the mean flow velocity through the reservoir. Brune (1953) developed a graphical curve (Brune curve) consisting of three curves; one median and two envelopes (fine and coarse sediment) to determine the trap-efficiency of a reservoir. 44 records of reservoir trap-efficiency and the factors affecting trap-efficiency were studied. It was concluded that the capacity-inflow ratio has a good correlation with trap-efficiency in comparison to capacity-outflow ratio but it may vary with the location of outlets and reservoir operating procedure. Borland (1971) concluded that Churchill curve is superior to Brune curve for estimating the trap-efficiency of desilting and partially dry reservoir. Though Churchill curves give better result than Brune curves to predict the trap efficiency of a reservoir, yet it is inconvenient to obtain the input data for determining the sedimentation index. Hence, Brune curve is used mostly in comparison to Churchill curve. According

to Vanoni (1975), trap-efficiency depends on sediment characteristics, stream flow velocity and reservoir operation. Rowan et al. (1995) showed that the trap efficiency calculated using Heinemann curve (1981) is 30 % lower in comparison to Brown curve (1944) for one reservoir, whereas with Brune (1953), it was in between the two. Figure 1 shows different curves for predicting trap-efficiency of a reservoir. Many empirical studies (Dendy 1974 and Gill 1979) correlated water inflow, reservoir storage capacity and trap-efficiency. Verstraeten and Poesen (2000) developed an empirical formula to estimate trap-efficiency of a reservoir but it needs more input data. In case of empirical models, prediction of trap efficiency for conditions without permanent storage are not accurate in contrast to physically based as well as numerical models, due to the inability of these empirical models to simulate consecutive runoff events.

Garg and Jothiprakash (2010) investigated the efficiency of conventional empirical approaches along with soft computing data-driven techniques such as artificial neural network (ANN) and genetic programming (GP) to estimate the reservoir trap-efficiency by incorporating reservoir age. It was found that ANN model results are better than conventional empirical methods but inferior to GP. Various investigators (Neil and Mazari 1993; Verstraeten and Poesen 1999) have concluded that sediment trap efficiency is an important parameter to assess sediment yield when sediment deposits in reservoirs. If trap-efficiency is not accounted for in such studies, sediment yield will be underestimated. Numerous studies on trap-efficiency of different reservoirs have been carried out by various investigators (Heinemann 1981; Villegas and Schnoor 2009; Stephen et al. 2013).

Sediment distribution

WCD (2000) reported that reservoirs all around the world are filled up approximately at a rate of 1 % every year. The annual storage loss of reservoir in terms of percentage for India is 0.46 (Chaudhry et al. 2014). The distribution of sediment particles at different elevations is based on factors like quantity of stream flow and mobility of sediment particles, physical and chemical properties of sediment and the operational procedure of a reservoir (USBR 1987). Churchill (1948) was the first to predict the reservoir sedimentation rate by relating the reservoir capacity loss with basic hydrodynamic parameters through empirical curves. Most convenient methods to determine the sedimentation of a reservoir are the direct measurement by hydrographic survey and the indirect measurement using the inflow-outflow records of a reservoir. But these methods are inconvenient, time consuming and uneconomical According to the traditional hydrographic survey, the storage

Fig. 1 Curves for predicting trap efficiency
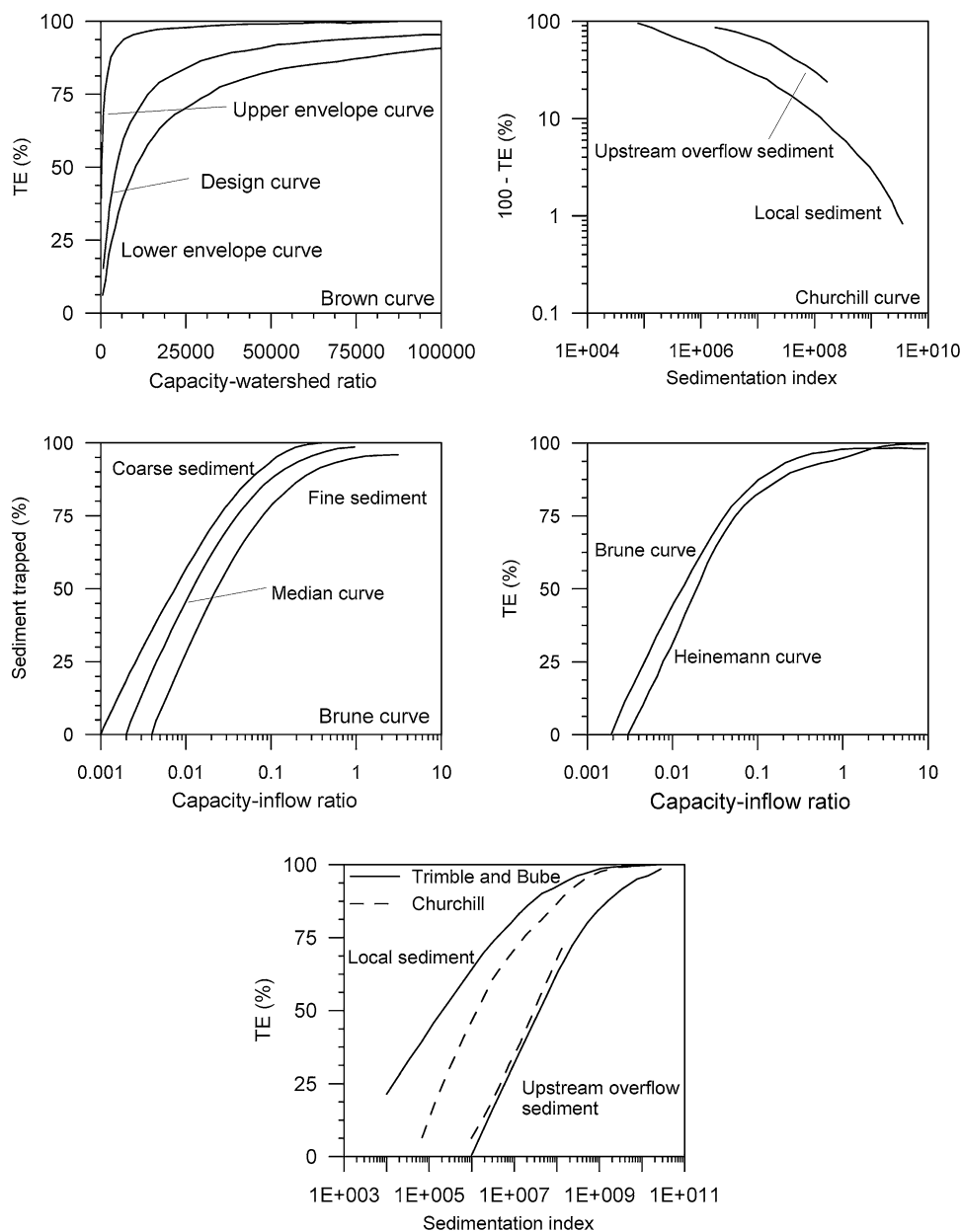
$V_{S(p+1)}$ of a reservoir at the water level h_{p+1} is expressed in the following form:

$$V_{S(p+1)} = \sum_{q=0}^{p} v_{S(q+1)} \qquad (24)$$

where

$$v_{S(q+1)} = \left(A_{res(p)} + A_{res(p+1)} + \sqrt{A_{res(p)}A_{res(p+1)}} \right) \Delta h/3 \qquad (25)$$

Δh = difference between two consecutive water levels of a reservoir, $A_{res(p)}$ and $A_{res(p+1)}$ = corresponding water surface area of h_p and $h_{(p+1)}$; and $v_{S(q+1)}$ = change in storage

of a reservoir in between two water levels Δh. Figure 2 shows the schematic of sediment distribution in the traditional method. Cristofano (1953) developed the area increment method to calculate the surface area of reservoir at any depth. It is based on the assumption that the volume of deposited sediment per unit height of reservoir is constant. The following expression represents the area increment method to predict the total sediment volume in the reservoir:

$$V_S = A_{res(0)}(H - h_0) + V_0 \qquad (26)$$

where V_S = total sediment volume, $A_{res(0)}$ = original reservoir surface area at depth h_0, H = maximum depth of
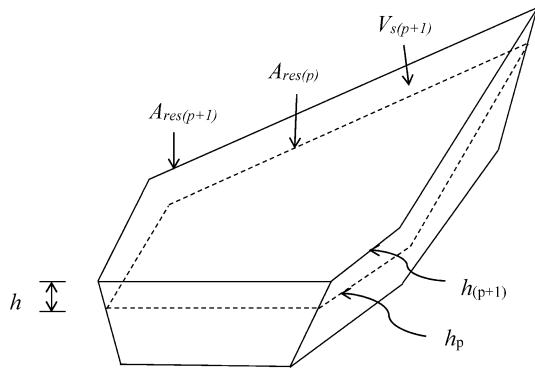
Fig. 2 Schematic of sediment distribution in the traditional method

Table 3 Values of C', m' and n' for four types of reservoirs (Borland and Miller 1958)

Type	C'	m'	n'
I	3.4170	1.5	0.2
II	2.3240	0.5	0.4
III	15.882	1.1	2.3
IV	4.2324	0.1	2.5

Table 4 Classification of reservoir (Borland and Miller 1958)

M	Reservoir type	Standard classification
3.5–4.5	Lake	I
2.5–3.5	Flood-plain-foothill	II
1.5–2.5	Hill	III
1.0–1.5	Gorge	IV

reservoir, h_0 = sediment depth at dam's wall position (new zero depth of the reservoir) and V_0 = original reservoir capacity at depth h_0. The Borland and Miller method (1958), also known as the area reduction method, was developed to express the sediment distribution at any level (h_0) above the bed. The equation of area reduction method is expressed as

$$V_S = \int_0^{h_0} A_{res} dh + \int_{h_0}^{H} k'' a_{p'} dh \qquad (27)$$

where A_{res} = reservoir surface area at any depth h, dh = incremental depth, k'' = constant of proportionality for converting relative areas $a_{p'}$ to actual areas. The equation of relative area is expressed as

$$a_{p'} = C' \times \bar{h}^{m'} \times (1 - \bar{h})^{n'} \qquad (28)$$

where relative depth $\bar{h} = h_0/H$; and C', m' and n' are coefficients, values of which depend on the type of the reservoir as presented in Table 3. The classification (gorge, hill, flood plain-foot hill and lake) of reservoir depends on the value of shape factor M. M is the reciprocal of the slope of the best-fit line resulted from the graph of reservoir elevation above bed as ordinate versus reservoir capacity at that elevation as abscissa on a log–log scale. Table 4 represents the classification of reservoir and Figs. 3 and Fig. 4 show the schematic of sediment distribution in the area increment method and area reduction method. However, in estimating reservoir sedimentation and accumulation, a number of uncertainties arise. These are related to quantity

Fig. 3 Schematic of sediment distribution in the area-increment method
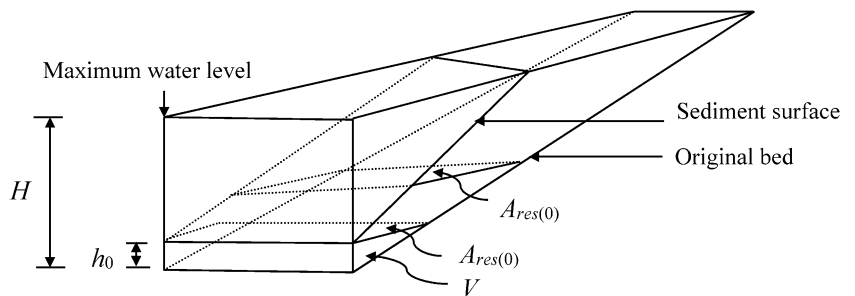
Fig. 4 Schematic of sediment distribution in the area-reduction method
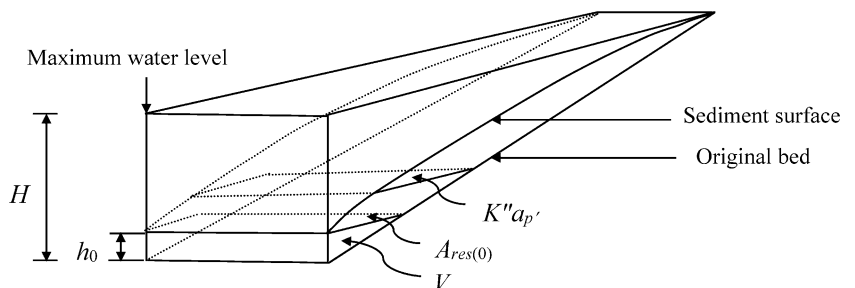
of streamflow, sediment load, sediment particle size, and specific weight, trap efficiency, and reservoir operation.

A number of mathematical models based on the equations of motion and continuity for water and sediment for predicting reservoir sedimentation have been developed by different investigators (Chen et al. 1978; Soares et al. 1982; and Morris and Fan 1998). Al-Taiee (2005) used a methodology to deal with the distribution of sediment particles on the bed of reservoir. But the above method does not provide good results, in case the maximum water level of reservoir is increased or the accumulated sediment particles are dredged. Physiographic soil erosion–deposition model (PSED), developed by Chen et al. (2006) is capable to predict sediment yield in the watershed and the sediment deposition in the reservoir. In this model, the computational cells are categorized into land form and river system by using the continuity equations for overland flow and suspended sediments. An empirical method independent of climate was developed by Md. Habili and Heidarpour (2010) relating the sediment distribution with the sediment volume and original reservoir characteristics. But they may not give good results if the accumulated sediments into the reservoir are dredged or maximum water level of the reservoir is increased.

Moldovanu et al. (2011) developed SEDCONTROL, depending on various factors like size and geometric shape of reservoir, geological structure of the hydrological basin etc. to estimate sediment deposition into the reservoir. The advantage of this approach is that it measures sediment deposition at a fixed position which is not influenced by the inevitable errors of mobile systems and also by the sedimentary material deposits on the walls. In addition, nowadays satellite data are used, which is cost and time-effective tool to determine the area-elevation and capacity of a reservoir (Jain and Goel 2002) and it has no influence on normal operation of a reservoir. Compared to other conventional methods, they are considered as superior so far as the change of water spread area of the reservoir after the deposition of sediment and distribution pattern of sediment at different elevations are concerned. However, the information of the dead storage capacity could not be obtained from remote sensing, but it could be obtained from hydrographic survey. Computer programs such as HEC-6 (U.S. Army Corps of Engineers 1993), Gstars3 (Yang and Simoes 2002), FLUVIAL and TABS (Morris and Fan 1998) have been developed to predict sediment distribution in reservoirs based on numerical solution using continuity, momentum and transport equations for both water and sediment.

Bed level

For monitoring the erosion and siltation processes in watershed and reservoir, one must have the knowledge of the changes of the shape of the reservoir bottom. The shape of the reservoir bed determines the depths in the reservoir as well as the volume of the accumulated water in the reservoir. The depth of accumulated sediment in a reservoir for a known period can be measured by using echosounder (an ultrasound source as emitter and transducer as receiver) and other electronic devices since the normal sounding operations give erroneous results for large depths. El-Manadely (El-Manadely 1991) developed a one-dimensional numerical model on the basis of momentum and sediment continuity equation to estimate change in the river bed profile in the longitudinal direction. Various publications are also there to determine the bed level of a reservoir by different techniques, such as Langland and Hanely (1997); Ceylan et al. (2011). Van Rijn (2006) mentioned that there are three methods for accurate measuring of bed level; bed level detection in combination of mechanical and DGPS (Differential Global Positioning System), bed level detection with acoustic bed level detectors (single and multi beam echo sounders) and bed level detection optically. Fuska et al. (2014) developed the method of reservoir bottom mapping for the determination of water depth and volume in GIS environment using 3D models of the reservoir bottom in raster and vector formats. However Moody's method (IS 5477-PART 2 1994) is also used to determine the new zero elevation which is defined as the raised bed level of the reservoir due to the deposition of the sediments.

Scope of future work and conclusion

This review, a preliminary research and also limited to some extent as it tries to cover huge periphery of soil erosion, sediment yield and sedimentation of a reservoir. It will help the readers to take prior consideration for assessing the soil erosion and sedimentation in reservoir.

Large numbers of research works have been done on soil erosion, sediment yield and sedimentation in various reservoirs and all research works guide us to understand the practical importance of the sedimentation problem. However, it remains unexplored from different aspects. Research on erosion process, sedimentation as well as their modelling approaches is still ongoing. Models that are capable to correlate both erosion and sedimentation at the basin scale have not been explored for reservoir. Different approaches may be developed to predict the effect of future climate change on sedimentation of reservoir. Relationships between upstream and downstream of a reservoir can be established by studying the complex phenomena of soil erosion, sediment yield and sedimentation of a reservoir. Research on water quality impact of sediments on water availability is also expected.

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