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Sources of Sediment and Process of Erosion

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Abstract : *Water erosion is the most widely spread degradation process on the earth through which not only the fertility of soil greatly decreases but, in many cases, the soil is physically destroyed and disappears. Although the problem of soil erosion has been concern of mankind since the dawn of settled agriculture, an understanding of the mechanism underlying these processes is still incomplete. In the last two decades, considerable progress has been made in unfolding the basics of erosion and sedimentation phenomena. This has been made possible because of advent of fast computers, availability of better instrumentation techniques, stress on field experiments, developments of newer techniques like remote sensing, and numerical methods etc. The paper brings out the physics of erosion-sedimentation process, mechanism of water erosion and various assessment techniques of the processes. A detailed amount of various models available for erosion & sedimentation processes have been mentioned. The status of reservoir sedimentation in India and its impacts have been elucidated. The need for research in the area has been brought out pointwise. It has been concluded that there is an immediate need to use powerful newer techniques like remote sensing and digital computer for estimation and extent of water erosion in various scenarios. It has also been stressed to conduct studies on large catchments with a view to develop soil-water land-vegetation interactions. As an important conclusion it has been pointed out that before taking up any soil-water conservation programme, it would be imperative to understand erosion process, various factors influencing erosion and estimate the magnitude of erosion, This would be all the more necessary for large catchments. Transposing of results from small watersheds to large catchments is not desirable considering the implications of hydrological phenomena. This calls for the use of extension monitoring utilising the modern technologies and use of mathematical modelling.*

1.1 Introduction

Soil and water have always been vital for sustainable life, and these resources are becoming more limited as population increases. The importance of conserving soil productivity and protecting the quality of both soil and water is becoming more clear to the people than ever before. The soil is a replaceable basis of agricultural production. The soil degradation by erosion effects enormous areas of the world. Nearly 31% of the land surface of the globe is subjected to water erosion. It washes about 60 million tons of the soil to the oceans every year.

Watershed plays a significant role in the development of any country. The main water related natural resources of a watershed are water, land, soil and vegetation. Depending upon the location of a watershed, they yield water for domestic, agricultural and industrial uses, produce a variety of wood products, contribute forage for livestock and wild life, and provide many forms of asthetic and recreational uses.

Land, water, soil and vegetation constitute an important part of the natural resources of a watershed. In many instances and situations, use of only one or two watershed resources products may lead to some sort of environmental imbalance. Hence it is important that an efficient and integrated development of the resources is manipulated to ensure sustrained yield for avoiding conditions of imbalance. Research is contributing in the area of watershed hydrology and it is oriented to provide adequate procedural approach and valuable data for quantifying the effects of soil erosion, yield and quality of water. While research is progressing towards this end, there is much we already know and use from past research, The land-water engineer, by necessity, must utilize the best information now available in order to satisfy present requirements for resources protection, development and planning.

Land, soil and vegetation relationships related to the properties of soil, land use changes, and vegetation management effect the movement, retension and use of water. Such relationship can definitely give a clue to impact of vegetation management on soil erosion and water yield. The interaction with soil and land use changes by vegetation management has been carefully investigated in developed countries. It has been found that though changes in vegetation on a watershed, it is possible to reduce soil erosion losses. There is a definite need for studying the intricate relationships amongst soil, water, vegetation and land to arrive at integrated quantifications of micro-and macro land. Excellent studies have been carried out on soil-water; water-land; soil-vegetation and vegetation-water interactions but there is an urgent need to take up soil, land, water-vegetation interaction studies. Also, a large amount of data are available on small watersheds and field scale plots but very limited studies have been attempted on large catchments. Also while transposing results of small watersheds to large catchments, there are possibilities of arriving at erroneous results.

1.2 Extent of Problems of Erosion/Sedimentation and Impacts

To stress the importance of erosion process on the globe many references to the increasing significance and severity of soil erosion and related sediment problems throughout the world have been quoted by authors (Walling, 1989). An indication of the magnitude and significance of the problem is provided by the following statements :

— Since the beginning of settled agriculture, soil erosion has destroyed about 430 million ha of productive land (Kovda, 1988).

— The annual global loss of agricultural land due to soil erosion is 3 million ha Buringh, 1981).

— The world is now losing an estimated 23 billion tons of soil from croplands in excess of new soil formation. At the current rate of excessive erosion, the global soil resource is being depleted at 0.7 per cent each year, 7% each decade (Brown, 1964).

— For every pound of food consumed in the United States in 1977, water caused lhe erosion of over 20 lbs of soil from all agricultural land (Clark, 1985).

— Crop productivity is reduced to zero or becomes uneconomic because of soil erosion and erosion-induced degradation on about 10 million ha each yr (UNEP, 1980).

— Crop yields from rainfed areas might decrease by 29 percent over the next 25 years (Higgins et al. 1982).

— Soil erosion in Kenya during the 1970's produced an economic loss greater than the value of the annual gross national product (SIDA, 1982).

— If present siltation rates continue, about 20 percent of the Nation's (USA) small reservoirs will be half-filled with sediment and in many instances, their utility seriously impaired in about 30 years (Dendy, 1968).

— In Pakistan, soil erosion and deposition have decreased the life expectancy of the 600 million dollar Mangla reservoir, planned to last 100 years or more to 57 years of less (El-Swaify et al. 1982).

— The annual off-site damage caused by sediment eroded from the land in the United States is estimated at more than 6 billion dollars (Clark, 1985).

1.3 Mechanics of Soil Erosion Process and Sediment Transport

Soil erosion and sediment by water primarily involve the process of detachment, transport and deposition of sedimenf by raindrop impact and flowing water. The dislogding of soil particles from the soil mass is detachment. Transportation is entrainment and movement of detached soil (sediment) from their original location. The sediment travels from upland through stream and may be deposited in the way or reaches into the reservoir or ocean.

Our ancestors used to believe that water erodes the soil when it flows on the surface in the form of surface runoff. But today this idea has been proved to be most wrong. Because investigations have shown that most of the erosion damage done by water is due to impact of falling raindrops. The erosion capacity of surface runoff is very small and it acts only as a partner.

The severity of erosion depends up in the quantity of the material supplied by detachment and capacity of eroding agent to transport it. The energy available for erosion takes two forms; potential and kinetic. Potential energy (PE) results from height difference of one body with respect to another.

$$PE = mgh \qquad (2.1.1)$$

where, m = mass of eroding agent (kg)

h = height difference (m)

g = acceleration due to gravity (m/sec

PE = potential energy (kgm m^2/sec^2)

The P.E. for erosion is converted into kinetic energy (KE). This related to the mass (m) and velocity (v) of the eroding agents

$$K.E. = \frac{1}{2} mv^2 \qquad (2.1.2)$$

Unit of KE is kg^{-m^2} / sec^2

Morgan (1977) reported that most of this raindrop energy is used in detachment, however, so that the amount of energy available is less than that from overland flow. This is illustrated by measurements of soil loss in the field in mid-Bedfordshire. In a study over 900 days period on a 11°22′ slope on a study soil transport across one centimetre width of slope amounted to 1900 gms of sediment by rills, 400 gms by overland flow, and only 50 gms by rainplash,

1.3 1 Rainsplash erosion

Rainsplash occurs essentially as a result of water drop impact forces. The downslope component of the momentum of falling rain drop on sloping land is transferred in full to the surface but only small portion of the component normal to the soil surface is transferred, the remainder being reflected. This transferred momentum provides a consolideting force to soli particles, compacting the soil and it imparts velocity to soil particles, Thus raindrops are agents of both consolidation and dispersion. The consolidation results from the clogging of the pores by soil compaction, where as the dispersion is associated with detachment and translocation. Detachment of soil partlcles by splash is expressed by the equation

$$\text{splash detachment } (E_{sd}) = a.K.E.^{b} \quad (2.1.3)$$

where, E_{sd} = splash detachment of sediment (gm/m^2)

K,E. = kinetic energy ($Joul/m^2$)

a&b = constants

1.3.2 Erosion by ovarland flow :

Overland flow detaches the soil particles when its erosive hydro-dynamic forces exceed the resistance of soil to erosion. The hydraulics of overland flow is given by Reynold number (Re) and its Froude number (F)

$$R_e = \frac{V_o r}{v} \quad (2.1.4)$$

$$F = \frac{V_o}{g.r} \quad (2.1.5)$$

where

r = hydraulic radius equal to the flow depth

v = kinematic viscosity of water

V_o = velocity of flow

On the basis of above D'Souza et al. (1976) concluded that for Reynold number less than 500, laminar flow prevails and for above 2000 the flow is fully turbulant.

Overland flow with Froude number less than one the flow is subcritical and the values greater than one denotes supercritical flow or rapid flow which is more erosive. It was reported by Emmett (1970)

The velocity of flow is tne important factor in relation to erosion and sediment transport. Meyer (1965) compared the continuity and Manning's velocity equation for a constant roughness coefficient and found that

$$V = S^{1/3} Q_w^{1/3} \quad (2.1.6)$$

With the help of above Carson (1972) suggested an equation to determine sediment discharge sediment discharge per unit width

$$Q_s = 0.0158\, Q_w^{1.75}\, K^{-1.11}\, (\sin\theta \cos\theta)^{1.625} \quad (2.1.7)$$

where, V = velocity of flow

S = slope percentage

Q_w = water flow rate or discharge

K = particle size of surface material at which 84% bed particles are finer

θ = gradient angle

A change from one type of overland flow to another flow results from more rain reaching the ground surface, less being intercepted by vegetation and decreasing infiltration as rainbeat causes a surface crust to develop soil erosion.

1.3.3 Sub surface flow

The sub surface flow of runoff washes the finer particles when it moves through pore space in the soil. Roose (1973) reported that soil water contributes only 1% of total material eroded in the hill side and it is mainly in the form of colloids and minerals in the ionic solution. Sub surface flow is more important however, than this figure suggests because the concentrations of base mineral in the water are twice than those found in the surface flow. Essential plant nutrients, particularly those added in fertilizer can be removad by this process.

1.3.4 Rill and gully erosion

The rain water flows over the land surface through the paths of least resistance and thus surface flow with its silt in suspension make the microchannels called rills. The transport and detachment capacity are both greater in rill erosion than sheet erosion. The amount of soil particles detached by moving water is proportional to the square of its velocity and ability of moving water to transport soil varies as fifth power of its velocity. Foster et al. (1975) estimated that about 87% of sediment transported by rills may be derived from overland flow and rain drop splash and the reminder is from inter-rill areas.

Gullies are relatively permanent channels with steep-side slope which experience concentrated super critical flow. Some of the soil particles are detached from the scrap itself but most of the erosion is particles with scouring at the base of the scarp which results in deepening of the channels and undermining the head wall. Sediment is also produced further down the gully by stream bank erosion.

1 4 Relationship between Soil Erosion and Sediment Deposit

The relationship between the amount of soil eroded at some upstream point and water borne sediment delivered to a downstream location is important for designing hydrological planning water resource development, and determining water pollution loadings. The principal sources of the waterborne sediment are sheet (also called 'interrill') and rill erosion on agricultural, forest, and range lands. Other sources are upland gullies, arroyos and valleys, stream channels, roads and highway ditches, various construction sites, and surface mined areas. In most instances, the eroded soil is deposited nearby so the net loss to an area is little or nothing.

The eroded soil that reaches stream channel and thereby becomes sediment yield from an area. Material removed from its position at a single spot on the landscape follows a slow, halting, devious course as it is transported from the land to the oceans.

The sediment yields of the major rivers of the world have been estimated (Holeman, 1968) They range from more than 7000t km^{-2} $year^{-1}$ for tributaries of the Yellow River in China; to 420-490 for the Yangtze, Indus, and Meknong; to less than 100 for the Mississippi, Amazon. and Nile. In Europe the suspended sediment yield of the Dnepre, USSR; Rhine, Holiand, Loire, France; and Oder, Poland all are less than 3,5t km^{-2} $year^{-1}$. The River Seine in Paris, has an average load of 25t km^{-2} $year^{-1}$ (including bed load) and the Arno. and Po, Italy, about 280t km^{-2} year Table 1 shows data which were extrapolated by Holeman (1968) giving the world sediment yield to the oceans.

Table 1

Total sediment delivery to oceans (adopted from Holeman, 1968)

Continent	Total area draining to ocean (10^6 km^2)	Annual suspended sediment discharge (t/km^2)	(10^9 tonnes)
North America	20.7	86	1.78
South America	19.4	56	1.09
Africa	19.9	24	0.48
Australia	5.2	40	0.21
Europe	9.3	32	0.30
Asia	26.9	540	14.53
Total	101.4	778	18.40

The erosion process begins when soil particles or aggregates are detached from the soil matrix. This requires energy that may be supplied by raindrop splash, runoff. seepage forces, and the grgvitational effect, (Onstad and Moldenhauer, 1975). The impact energy on the soil of 760 mm of annual rainfall on an area of 1 km^2 is tremendous and has been estimated as equivalent to that released by exploding 3500 tonnes of TNT (Meyer, 1972).

Meteorological factors effect erosion and sediment yield in several ways Year-to-year or storm-to-storm precipitation differences, for example, often account for larger variations in sediment yield from mixed cover basins than most other factors (American Society of Civil Engineers 1075). The form and intensity of precipitation at different seasons of the year along with antecedent soil conditions are of primary importance in sediment production.

Rainfall distribution plays an important role in basin soil loss and sediment delivery (Onstand and Moldenhauer, 1975). For example, a high intensity storm near the outlet could cause more sediment yield than the some storm in the upper part. Seasonal distribution of rainfall is very important because soil distribution is markedly affected by the vegetative cover at the time of erosion-producing rainfall. Long-duration low intensity rainfalls are less erosive than short-duration intense storms.

The important factors affecting sediment yields are size of drainage area, topography, soils, cover conditions, and degree of channelization. The larger the drainage area in a given physiographic area. the larger the total sediment yield. However, the sediment delivery ratio decreases as the size of the drainage area increases (Table 2). The sediment ratio is defined as the percentage of the sediment delivered at a location on the stream system to the gross erosion on the basin. Gross erosion is usually determined by applying the universal soil loss equation (Wischmeier and Smith, 1965) for upland erosion and estimating the amounts from other sources.

Table 2

Effect of drainage basin size on sediment delivery ratio (adopted from page 460, American Society of Civil Engineers, 1975)

Drainage area (km^2)	Sediment delivery ratio (%)
0.1	53.0
0.5	39.0
1,0	35.0
5.0	27.0
10,0	24.0
50,0	15,0
100.0	13 0
200,0	11.0
500.0	8.5

With large basins the distance of sediment transport downstream is greater as is the opportunity for deposition enroute, so the size of the drainage area is important in the total sediment yield. Many other factors, like rainfall, plant cover sediment texture, and land use, complicate this relationship. Therefore, all of these factors must be evaluated in estimating volumes of sediment from an erosive source. deposition in a proposed reservoir, or sediment yield to downstream locations (US Department of Agriculture, 1971).

The largest percentage of sediment produced by erosion is derived from sheet erosion from tilled lands, and some from vegeted non-tilled lands. Conservation practices have reduced sheet erosion from upland areas. However. in some areas, runoff from conservation treatment areas has greatly increased channel erosion. In some locations, erosion from specialized activities, like urban development, factory and heavy construction and strip mining, is becoming increasingly importnnt.

In addition to rainfall variability, the soil and vegetation parameters also influence sediment yield, Soil erodibility is determined by many factors, incluping soil texture and organic matter. Tillage methods and residue management influence the amount of soil erosion. Residue and mulches reduce runoff by providing cover and reducing surface sealing and crusting Erosion reduction is a direct function of the percentage of an area covered by mulch.

The gross erosion prediction results are multiplied by the sediment delivery ratio for estimating the amount of sediment delivered to a downstream point. For this, the delivery ratio concept provides an empirical reduction ratio and also integrates effects of channel and flood-plain erosion and deposition in valleys below the eroding slopes.

Gullies are a source sediment that must be considered in the relationship between soil erosion and sediment delivery. The concentration of runoff encourages gully formation which is common in most regions, and is usually associated with severe climatic events improper land use, or changes in stream base levels. Gully growth patterns can be cyclic, steady or spasmodic. Gully activity is significant in terms of quantities of sediment produced and delivered to downstream locations in regions of moderate to steep topography with thick soil profiles. The total sediment outflow from eroding gullies, through large, is usually much less than that pruduced by sheet erosion. although the economic losses from dissection of uplands, damage to roads and drainage structures, and deposition of relatively infertile overwash on flood plains are disproportionately large (American Society of Civil Engineers, 1975).

Methods are not available far accurately predicting rates of gully erosion. Several localized equations are available for determining the sediment production from gullies, but these methods are quite approximate and questionable. The value of estimation procedures has often been limited because causative variables, like runoff, groundwater, and antecedent conditions, were not measured.

Streambanks can erode by direct or indirect action of flowing water. For example, (i) banks are undercut and collapse by gravity, (ii) flow impinges directly on the banks, and (iii) banks are saturated and weakened by streamflow or bank seepage. Additional factors contributing to streambank erosion are wave action, ice flows freezing action, wet-dry cycles, rapid changes in stage, debris, and sediment load.

In recent years, the amount of channel erosion has been considerable, particularly that from bank instability. Partly as a result of upstream conservation practices which have been instituted since the 1930s, stream channels in many areas are beginning to erode at a rapid rate. Conservation and erosion control measures in the uplands have reduced the supply of sediments entering the stream channels. A stream flowing in erodible materials presents a delicate balance between transport and deposition. A flowing stream has the energy to carry a sediment load and if flowing over an erodible boundary, will pick up and carry a sediment load equal to its energy availability. Therefore, if its flow is clear on entering the erodible stream channel, then channel erosion will usually occur.

Under some circumstances, channel erosion can be very significant Accelerated streambed erosion can also trigger downcutting of tributary channels and gullies because it lowers the base level. Channel straightening and realignment measures, accompanied by clearing protective cover from banks, can accelerate streambank erosion through changes in slope and in stream competence to carry sediment. A straightened channel results in greater slopes and higher velocities. The stream is adjusted when its ability to transport sediment is decreased or part of its sediment load is deposited because reduction in slope or absorption of flow into a permeable channel bed. Many factors, such as bed slope, velocity of flow, suspended sediment being carried by the streams, cohesiveness of the bed and bank material, plant cover on the banks, and particle size of sediment available for the transport in the stream, control channel erosion (Pacific SW Interagency Committee, (1974), Channel erosion is a very sidnificant part of the sediment yield from basins in semi-arid areas. In evaluating long-term sediment yields, valley sedimentation and deposition between eroding areas and down stream points of sediment measurement or delivery must be considered. Much of the eroded soil deposits on the land before reaching defined channels. Over a period of many years these deposits may accumulate into sizeable valley depositional areas. To estimate down-stream sediment yield, the accumulation of sediments in the valley deposits must be determined.

1.5 Reservoir Sedimentation Prediction

The process of erosion and subsequent sedimentation in reservoirs brings in focus reservoir sedimentation. Hence it would be useful to discuss briefly the objectives of reservoir sedimentation prediction, Various uses/advantages of predicting sedimentation could be :

(i) To estimate the expected useful life of a reservoir which is most important criteria in the justification from the economic view point. The prediction would require an estimate of the average amount of sediment which would enter the reservoir and the part which would be trapped in reservoir.

(ii) As the cost of a planned water resources project would largely be influenced by the conservation methods to be employed at a later stage, it becomes imperative to include the expected sedimentation and its remedial cost in the economic analysis of the project.

(iii) To get an answer of the following questions :

(a) How soon will be reservoir be filled with sediments ?

(b) What will happen to stream below the dam ?

(c) What will the the effect of conservation measure on the stream channel ?

(d) What will be the total amount of sediment which will be retained in a certain period of time ?

(e) What will be locations of such deposits ?

Here it would also useful to give the standard terminology, normally encountered in the literature concerning life of reservoir. These could be :

Useful life : It is generally taken as the period through which the capacity occupied by sediment does not prevent the reservoir from serving its intended primary purposes. It is taken to be terminated when another reservoir has to be built to assist it to meet the commitments,

Economic life : This is found by the point in time, when the effect of various factors causes the costs of operating the reservoir to exceed the additional benefits to be expected from its continuation. These factors could be depreciation by sedimentation, risk and uncertainty etc

Useable life , Tha reservoir can serve some of its intended purposes even after the expiry of its economic life.

Design life : This is the life span as given by agency responsible for design. Generally it is 50 to 100 years.

Full life : It is the number of years required for the reservoir capacity to be fully depleted by sedimentation.

Various objectives of predicting reservoir sedimentation could be at various stages the :

(i) In planning stage
(ii) In design stage
(iii) In operation stage

Here it would be relevant to mention various factors affecting silting in reservoirs, these could be :

(i) Catchment area and its various zones (topographical)

(ii) Monthly and annual rainfall in various zones

(iii) Snow fall volumes and characteristics

(iv) Mean monthly temperature in various zones

(v) Slope of the catchment

(vi) Vegetation cover and land lose pattern

(vii) Geological formation of each zone

(viii) Silt entrapped by upstream reservoirs

(ix) Trap efficiency

(x) Catchment inflow ratio

(xi) Type of sedimentation course medium and fine

(xii) Density of silt and degree of consolidation

(xiii) Total silt accumulated per year

(xiv) Reservoir operation criteria

(xv) Type and shape of reservoir

(xvi) Water currents

(xvii) Residence time in reservoir.

1.6 Avenues for Research

1. The effects of raindrop impact in causing soil detachment and the influence of the depth of overland flow and drop diameter on amount of soil splash are well established, however, uncertainity still remains as to whether drop impact can be expressed more effectively in terms of kinetic energy or momentnm. Extensive field data are required to be collected for answering this uncertainity.

2. There is a need to understand the interaction between discharge velocity and the resistance of a soil to erosion by flowing water.

3. The data base for developing meaningful relationships between slope length with slope gradient and form is still limited.

4. The indirect methods of finding soil erodibility needs to be put on firm physical basis.

5. There are some vital gaps in our knowledge and understanding of processes of rill / interrill erosion, and in particular of the transition between rill erosion and gully development.

6. The data base for defining 'climate aggressivity' is rather limited.

7. Well designed and adequately equipped studies are needed to quantify the effects of particle size distribution on soil erodibility.

8. A large amount of data are available on small watersheds end field size plots but very limited studies have been attempted on large catchments,

9. While transposing results of small watersheds to large catchments, there are possibilities of arriving at erroneous results.

10. Excellent studies have been carried out on soil water; water-land; soil vegetation and vegetation water inter-actions but there is an urgent need to take up soil-water-vegetation-land interaction studies:

11. There is need to take up extensive monitoring of large catchments utilising the modern technologies like computers, remote sensing and mathematical modelling

12. Any water resources, project would inevitably have a reservoir. The reservoir when constructed would have an important role to play in influencing the physical conditions of the river basin and thus effect the total environment of the area. It would also effect the economic and social environment of the area, This again stresses the need for studying in details the reservoir sedimentation process.

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