WORKSHOP

ON

RESERVOIR SEDIMENTATION ASSESSMENT USING REMOTE SENSING DATA

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Module 1

Remote Sensing
and
Grid Area Based Approach
to
Reservoir Sedimentation
Estimation

BY

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REMOTE SENSING AND GRID AREA BASED APPROACH TO RESERVOIR SEDIMENTATION ESTIMATION

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1.0 Introduction

Management of water resources often require construction of dams across rivers for creating storages and regulating flows. The practice is widely prevalent in the country due to vagaries of rainfall distribution both with respect to time and space.

Water flowing into a dam from surface run-off always carry sediments which settles down on the bed of the reservoir due to decrease in the velocity of flow. Continued deposition of sediments in course of time leads to reduction in the storage capacity of the dam and hence in the anticipated benefits. In some of the reservoirs constructed in earlier periods it is found from capacity surveys that the design assumption of sedimentation rate was quite low causing reduction in the useful life of reservoir (1). Analysis of sedimentation survey details in respect of 43 major, medium and minor reservoirs in the country indicate that the sedimentation rate varies between 0.3 to 27.85 ha. m/100 sq.km./yr. for major reservoirs to 1.0 to 2.63 ha.m./ 100 sq.km./yr. for minor reservoirs (2). Therefore, it is imperative that sedimentation processes including the rate of sedimentation are suitably accounted for in the design of a dam so that the reservoir will function at its optimum efficiency throughout its life span. Further, periodic investigations into the amount of sediment entering a reservoir are also necessary for maintaining operational efficiency of a reservoir. Therefore, both for the purposes of dam design and also for the maintenance of reservoir operations, estimation of sediment quantities entering a reservoir constitute an important aspect of water management.

Key-Note paper for the Workshop on Reservoir Sedimentation to be held at National Institute of Hydrology, Roorkee

2.0 Methods For Reservoir Sedimentation Estimation

Methods commonly followed for estimating reservoir sedimentation can be grouped into (1) Direct Measurement Methods and (2) Indirect Methods, summary details of which follow.

2.1 Direct Measurements

There are mainly two methods of direct measurements. The first is by conducting capacity surveys either by contour surveying or by range line survey. The second is by sampling the sediment load in the inflowing stream(s).

Capacity surveys involve taking soundings and developing the configuration of the reservoir bed and sides. By comparing the re-survey details with the original bed profiles (before the construction of the dam) the volume of the sediment deposited is calculated. The total volume of the sediment accumulated is converted to dry weight of sediment by determining the specific weight of the deposits. Further, by calculating the sediment outflow from the dam by measuring sediment concentrations in the discharges from the dam or by taking the estimated trap efficiency of the reservoir, the total sediment deposited for the period covered by the survey is determined. Based on this, estimate of long term sediment yield rate is obtained. Sediment yield is defined as that part of the total material eroded in the catchment which reaches the reservoir (3). Details of capacity survey for reservoirs may be found in reference (4).

Sediment yield rate can also be determined by periodic sampling of the stream flow to determine sediment concentrations for various discharges. The values of sediment concentration are plotted against the discharge to develop the sediment rating curve for the reservoir. Average sediment concentration for various discharges is then related to expected frequencies of different discharges in the stream to arrive at the long-term estimate of suspended load. To this is added the measured bed-material load to obtain the long term total sediment yield rate. Details of sampling methods and sediment load measurements, both in suspension and on the bed of the streams, are covered in reference (5). The method provides reliable estimate of long-term sediment yield rate provided that the sampling is representative of the variability of discharges expected over the period. Errors or bias associated with the use of sediment rating curves may be reduced by using non-linear regression technique (6).

2.2 Indirect Methods

Predicting sediment yield rate (1) based on comparison with similar catchments and (2) by using data on erosion and sediment delivery ratio, constitute the indirect methods.

The sediment yield rate to a proposed reservoir may be predicted by considering a rate equal to that measured on a nearby similar catchment. This method is reliable if both the catchments are essentially the same with respect to soils, topography, size, landcover and other conditions influencing erosion and movement of sediment (7).

The sediment yield rate can also be arrived at by estimating the gross erosion in the catchment and adjusting the quantity for the expected delivery ratio of the sediment to the reservoir site. Sediment delivery ratio (expressed in percent) is the ratio of the sediment yield to the total erosion and is dependent upon the physical features and hydrologic characteristics of the catchment. The physical features which have significant influence are the drainage area, slope and degree of channelisation. The hydrologic features that influence the ratio are the rainfall and run-off characteristics. While the erosion quantity for sheet and rill erosion is calculated using reliable equations such as, Universal Soil Loss Equation, the channel erosion is determined either by direct measurement methods such as, sediment-load sampling or by using equations that are based on flow regime theories such as Lacey's for Indian conditions. However, 'a review of the state-of-the-art of analysing reservoir sedimentation processes indicate that ... there are areas... still in need of better understanding' (8).

2.3 Remote Sensing Method

Remote sensing involves measurement of radiation reflected or emitted from the surface of objects. Sensors operating in different frequencies / frequency ranges of the electromagnetic spectrum provide information differently about the surface or shallow layers of objects they observe. For example, measurements of reflected solar radiation give information on albedo, thermal sensors measure surface temperatures and microwave sensors measure dielectric properties of surfaces. Since different objects have their own unique radiation characteristics the radiation measurements can be used to determine the properties of objects (9). Remote sensing in modern times refer to satellite based observations of earth surface and the synoptic view and repeated coverage available from a satellite are very valuable which no land based data collection method can match. Especially monitoring of large areas on a frequent basis can only be achieved economically with remote sensing.

The problem of reservoir sedimentation using satellite data can be approached in two ways. In the first approach the reflectance values of sediment laden water are correlated with the sediment concentrations for estimating the sediment load in the water body. In the second approach erosion from the catchment area is estimated using the land cover/landuse details from the satellite imagery and substituting the up-dated values for parameters in erosion estimation equations. Sediment yield is then obtained using the sediment delivery ratio value.

The first approach mentioned above has been successfully used in inferring water quality indicators, such as, colour, turbidity, chlorophyll content, etc. Estimating sediment concentrations in a waterbody constitute a specific case of satellite data use in turbidity measurements. There are many studies using satellite imagery data, both in digital and hard copy photo print forms, to relate suspended sediment concentrations in water with radiance values / reflectance (10, 11, 12, 13, 14, 15). However, a serious limitation to this approach is the failure of a satellite sensor to detect turbidity deeper than about

1 metre at the most in a waterbody (16). In addition, studies have shown that satellite data in the frequency range of 600 to 800 nm only show correlation with suspended sediments for concentrations upto 500 mg/litre. But for concentration levels greater than 500 mg/litre, satelllite data does not correlate with the sediment concentrations (17). Another problem is that much of the signal measured at the satellite point originate as atmosphere scattering (solar energy backscattered in the atmosphere without reaching water) (11). Further, for Indian conditions the sediment inflow to reservoirs take place generally during and immediately after the monsoon months. Obtaining cloud free satellite data during this period of heavy sediment inflow is difficult as the sky will be heavily overcast. Therefore, the second approach of using the satellite data for estimating erosion and sediment yield was followed in a study carried out for developing a methodology for estimating reservoir sedimentation based on remote sensing (23). The details of the study are covered in the following sections.

3.0 Erosion and Sediment Yield Estimation using Satellite Data and Grid-Area Approach

Erosion is essentially a two part process, the first being the loosening of the soil particles and the second their transportation. Primarily it is the sheet and rill erosions induced by raindrop impact and surface run-off that constitute the major components of the erosion loss from a catchment (18). A number of methods for assessing soil loss have been developed. Among them, the Universal Soil Loss Equation (USLE), an empirical model, is widely used to estimate sheet and rill erosion. The equation has been tested nation-wide in USA and in many places in other countries (including India) (19). The equation has been revised to more accurately estimate the soil loss from both crop and rangeland areas (20). The general form of USLE is

$$A = R.K.L.S.C.P. \qquad \ldots (1)$$

Where
A = Avg. Annual soil loss; R = Rainfall erosion index
K = Soil erodibility factor, L = Slope length factor
S = Slope steepness factor, C = Vegetative cover factor
P = Landuse management practice factor

Application of USLE to large catchments involve lumping of several parameters (21). To overcome this limitation square grids are superimposed over the catchment with the mesh size conditioned by the applicability of USLE (22). However, the approach while satisfying the condition of homogeneity of parameters, require large data bases. Hence, information system based spatial data processing technique appeared as a convenient method and was adopted. The method broadly involve generating a common and mutually compatible spatial format, namely, rasterised data planes. The rasters are created to a user defined cell size and initially kept blank. Different thematic features like landcover, slope, lithology, soil type, etc. available as polygons, lines and points are then tagged to the grids of a raster base each. In case the theme is already in raster form, such as landcover derived from satellite imagery, the same is tagged directly to respective grids by coordinate registration. In other cases, the themes are digitised, converted from vector to raster and then tagged to the grids. The details of the information system package developed for application are explained in reference 23 and fig. 1 shows the schematic representation of the modules comprising the package.

3.1 Study Area

The catchment of Nayagaon Nulla spread over an area of 17.8 sq. kms in the Kaum river catchment of the Godavari river basin in Maharashtra, was selected for testing the developed methodology. The Kaum river drains directly into the Nath Sagar reservoir formed by the Paithan dam across Godavari river near Aurangabad. The location of the study area is shown in Fig. 2.

3.2 Generation of Data Bases

3.2.1 Data Base for Slope

Contours from 1:50,000 scale Survey of India topographic map (47 m/5) were used to create the slope data base for the study area. The area bound by a contour and the catchment boundary or that between two consecutive contours and the boundary of the catchment constituted a

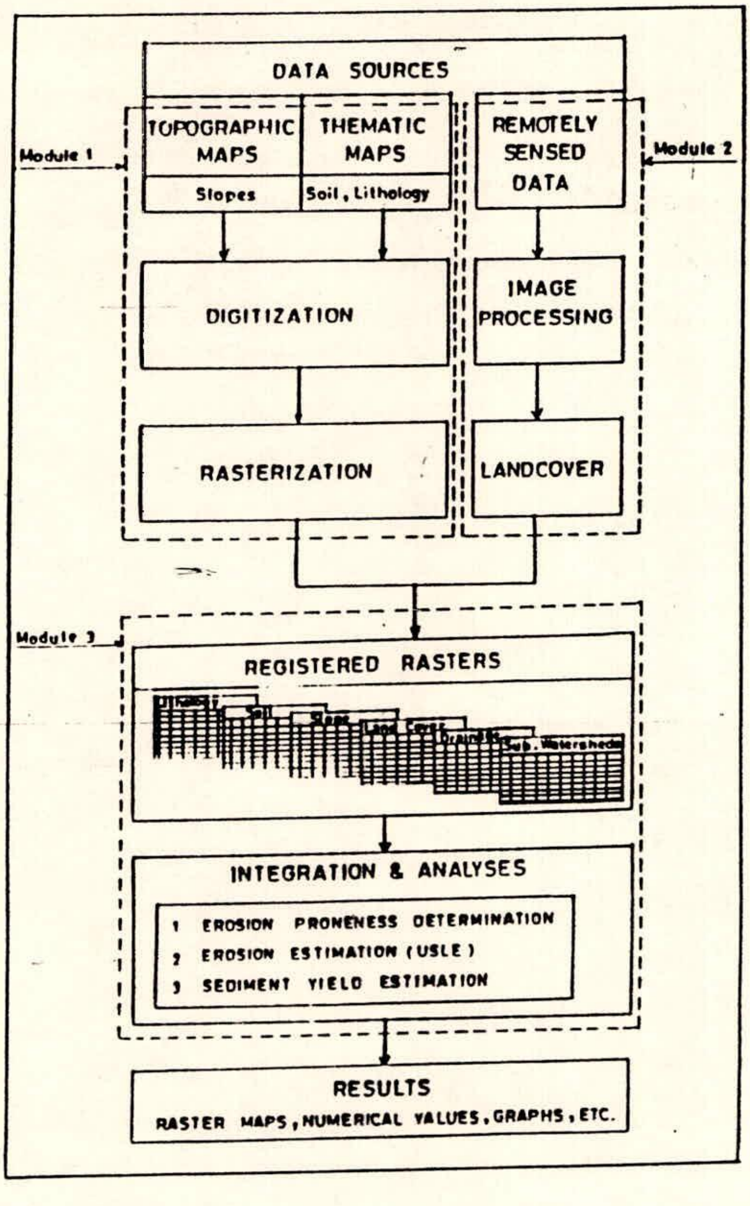


FIG. 1 MODULES OF THE INFORMATION SYSTEM PACKAGE.

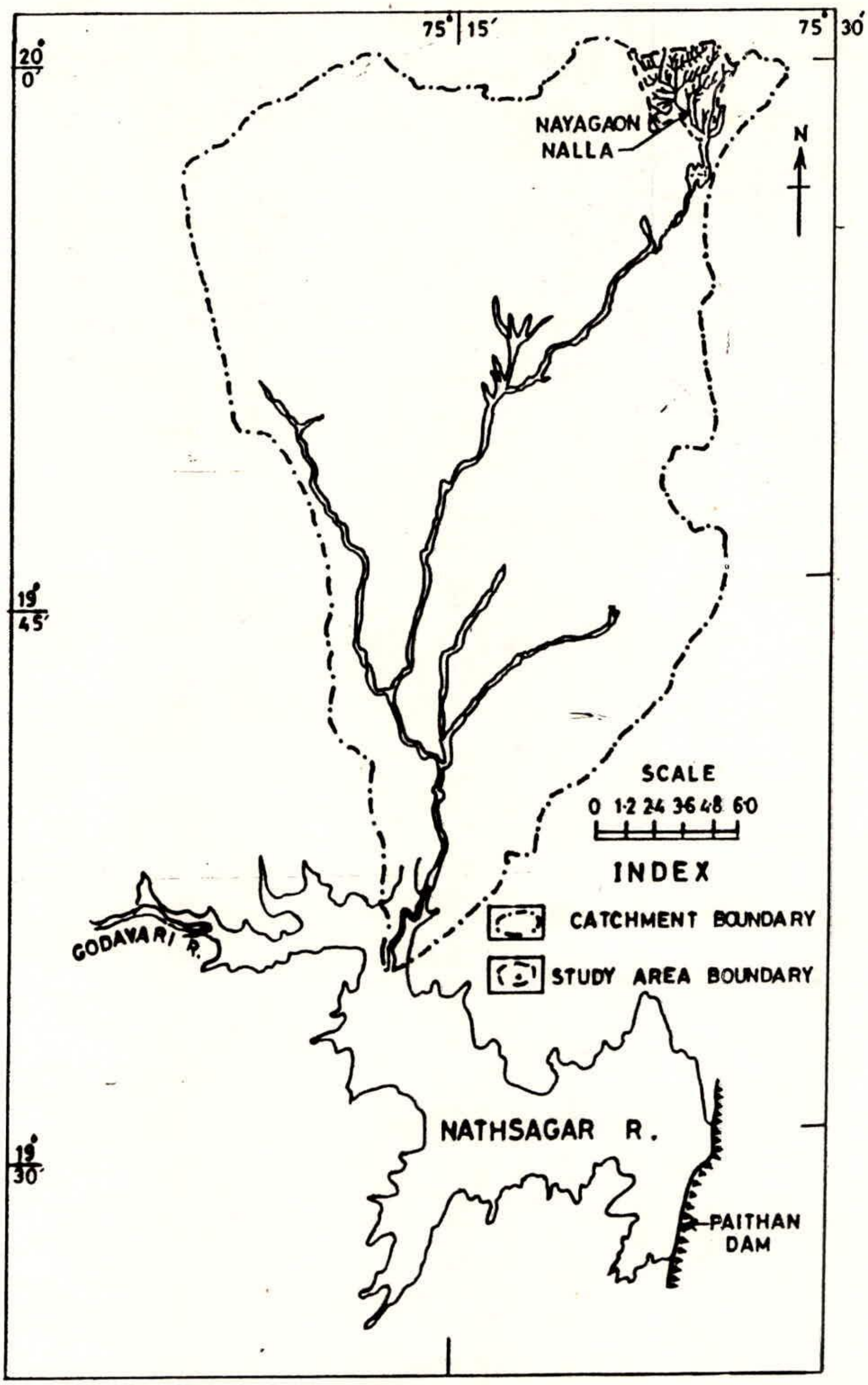


FIG. 2 LOCATION OF THE STUDY AREA

polygon. Points numbered sequentially on each contour line (to convert curve into a segment) constituted the nodes and were referenced to the rectangular grid. The coordinates of nodes for each polygon were processed separately line by line and a set of tables, one for each polygon, were created and then combined to form a single raster. The skeletonised polygons were then filled with character symbols representing the slope class. Fig. 3 shows the rasterised data base for the slope classes.

3.2.2 Data Base for LS

The slope length and slope steepness factors, L and S, is generally considered together and is defined as the ratio of the soil loss per unit area on a site to the corresponding loss from a 22.1 m (72.6') long experimental plot with a 9 percent slope (18). It is derived from Wischmeier's empirical equation given by

$$LS = \left(\frac{65.41 \, . \, s^2}{s^2 + 10{,}000} + \frac{4.56 \, . \, s}{\sqrt{s^2 + 10{,}000}} + 0.065 \right) \left(\frac{l}{72.5} \right)^m \qquad \ldots (2)$$

Where LS = Slope length - gradient factor

l = Slope length, ft (m x 0.3048)

s = Slope steepness

m = Exponent dependent upon slope steepness
0.2 for slopes < 1%; 0.3 for slopes 1 - 3%
0.4 for slopes 3.5 to 4.5% ; 0.5 for slopes > 5%

For the purpose of calculating the LS, two data bases were created, one for the 'S' factor and another for the 'L' factor, corresponding to the terms in the parenthesis of equation (2), respectively. The slope steepness, s, is taken as a ratio of the vertical to the horizontal. The slope length 'l' is taken as the maximum distance of a pixel in a sub-catchment from the local drainage line. For calculating the slope-length separate data bases for sub-catchments and the drainage lines were created as explained in Section 3.2.6.1. The data base created for S and L are shown in Fig. 4.

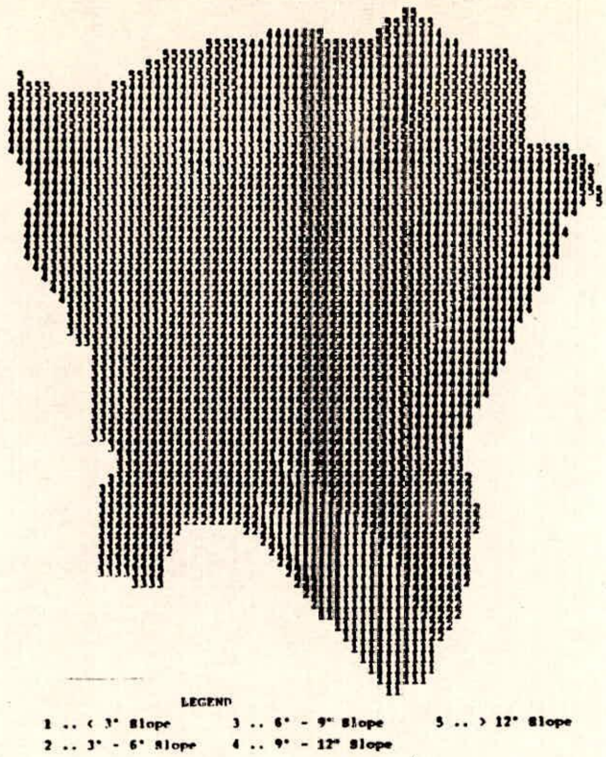


Fig. 3 Data Base of Slope Classes

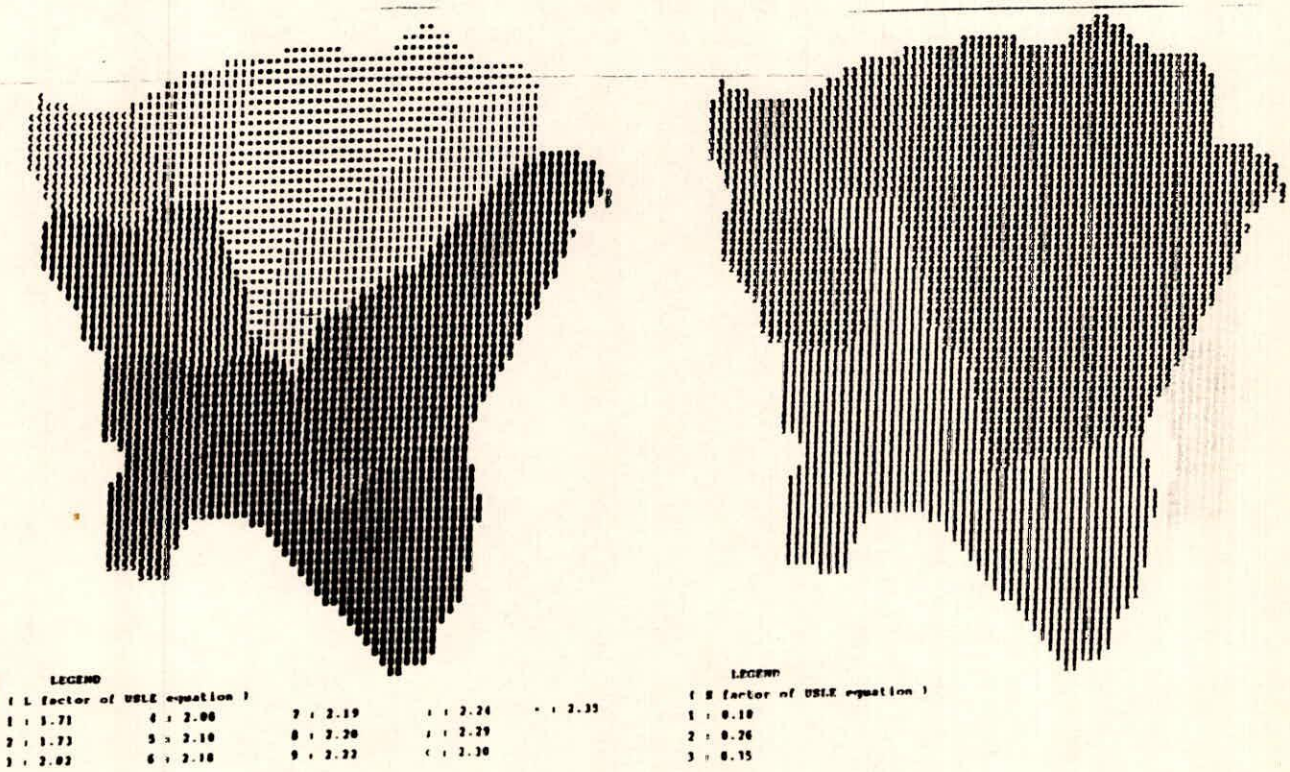


Fig. 4 Data Base of S and L Factors

3.2.3 Data Base for Soil Erodibility Factor - K

The soil erodibility factor, K, is a measure of the suceptibility of soil particles to detachment and transport by rainfall and run-off. Texture is the principal factor affecting K but structure, organic matter and permeability also contribute. K values are taken from triangular nomograph of percent sand, silt and clay. The soil at Nayagaon Nulla is reported to be of following composition (24).

Depth	Sand	Silt	Clay
0-5 cm	34.5	19.4	45.8
0-10 cm	29.0	25.0	45.2
0-15 cm	28.2	23.6	48.2

Referring to the nomogram of soil texture (18), the soil type for the Nayagaon Nulla is obtained as silty loam and the value for K as 0.26. Therefore, in the K factor data base, Fig. 5, a value of 0.26 is taken for the entire catchment and is denoted by K.

3.2.4 Data Base for Landuse Management Practice Factor - P

The landuse management practice factor, also called as the erosion control practice factor, P, is defined as the ratio of the soil loss with a given surface condition to soil loss with up-and-down-hill plowing. 'Changing the surface condition does not provide much direct reduction in soil loss and all the P values remain close to 1.0' (18). Therefore, a value of 1.0 is chosen for the P factor and the data base created by denoting the whole area by P as shown in Fig. 6.

3.2.5 Data Base for the Rainfall Factor - R

The rainfall factor, R, is determined by the following relationship given by Wischmeier and Smith (25)

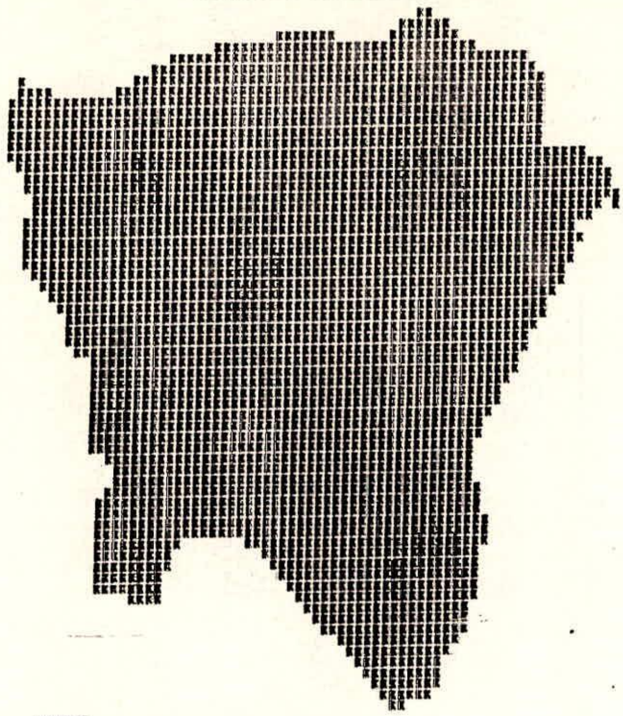


Fig. 5 Data Base of K Factor

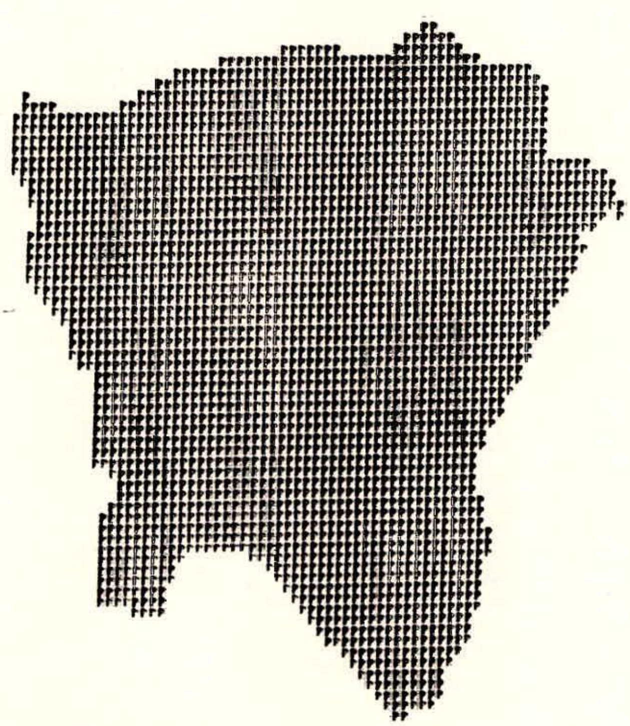


Fig. 6 Data Base of P Factor

$$R = \sum_{o}^{t} \frac{EI_{30}}{100} \qquad \ldots (3)$$

Where t = Period for which the soil loss is to be estimated

E = Kinetic energy in metre-tonnes/hectare centimetre of storm rainfall given by (25)

$$E = 210.3 + 89 \text{ Log } I \qquad \ldots (4)$$

I = Rainfall intensity in Cms/hr.

I_{30}= Maximum 30 minutes intensity of storm rainfall

The self recording raingauge station data of IMD at Chikalthana, near Aurangabad, for the year 1992 was used to determine the R factor. During 1992, there were four dates on which the rainfall intensity exceeded 30 mm/hr., the values of which alongwith E calculated from equation (4) above, are as follows.

Date	16.6.92	28.7.92	15.8.92	2.9.92
Rainfall Intensity In mm/hr	31.2	40.8	36.0	34.29
E	343.28	353.65	348.80	346.93

The value of R is then obtained from equation (3) as 248. Thus, for the rainfall factor a raster data base with a uniform grid value of 248 was created and denoted by 'R' as shown in Fig. 7.

3.2.6 Data Base for the Vegetative Cover Factor 'C'

The vegetative cover factor 'C' and the slope length and steepness factor LS are found to determine most of the spatial variability in soil erosion losses (21). Therefore, determining 'C' values accurately constitute an important step. The 'C' values are generally chosen by referring to tables listing the value for different vegetative cover type and landuse practices. But, it is essential that the landcover/landuse details are determined accurately for the purpose. The satellite data with its synoptic view and periodic availability constitute a convenient and reliable source of data for the landcover/landuse information. Therefore, to create the 'C' factor database, IRS-1A LISS-II sensor image for the scene 29-54-B1 of date 18.10.1990, available on CCT, was used. A window of 512 lines x 512 pixels from the starting line 1001 and starting pixel 889, was read from the CCT and classified first using the euclidean distance classifier and then the K-mean classifier. This was registered to the topographic map by polynomial interpolation. From this geometrically corrected sub-image a rectangle of 166 lines x 177 pixels starting from line 66 and pixel 235, containing the study area, was extracted. The pixel size of 36.25m x 36.25 m (resolution of LISS II image) in this rectangle was transformed to 80m x 80m using the resampling procedure, thereby reducing the size of the rectangle to 75 lines x 80 pixels to match with the study area frame. After registering the classified resampled image with the study area frame, the image pixels outside the boundary of the catchment area were masked to obtain the land features for the area within the test site. This is shown in Fig. 8 with the land features indicated by character notation. The 'C' values were assigned to the features on a sub-catchment basis after creating the database for the sub-catchments as follows.

3.2.6.1 Data Base for Sub-Catchments

One of the main limitations of the USLE for estimating soil loss from large catchments is that the value of parameters get lumped (21). This can be reduced by dividing the catchment into sub-catchments. Therefore, the sub-catchment boundaries delineated on the drainage map were digitised and registered with other data planes. Fig. 9 shows the division of the study area into 15 sub-catchments denoted by character notation. This sub-catchment frame was used for creating the 'C' factor data base and also the flow route network shown in Fig. 10. The latter was used for calculating the slope length 'l' in equation (2) (Section 3.2.2).

The 'C' values chosen for the landcover features of the study area on a sub-catchment basis are as follows:

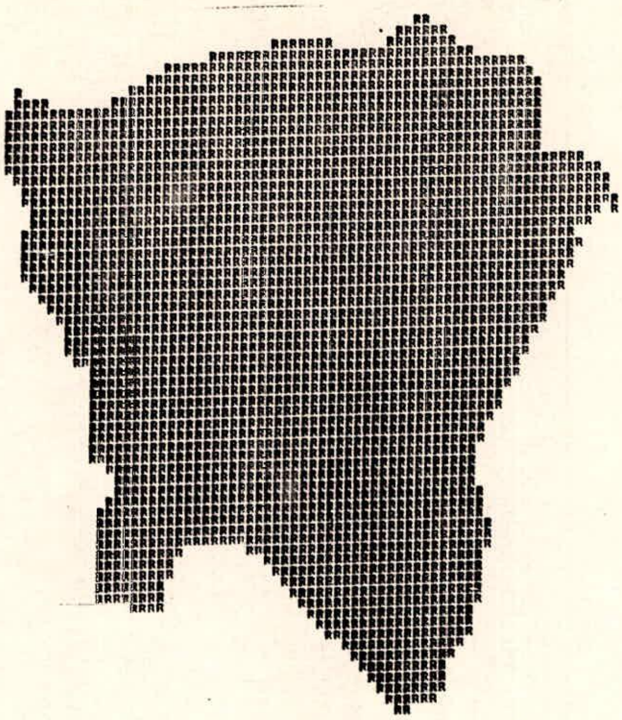


Fig. 7 Data Base of R Factor

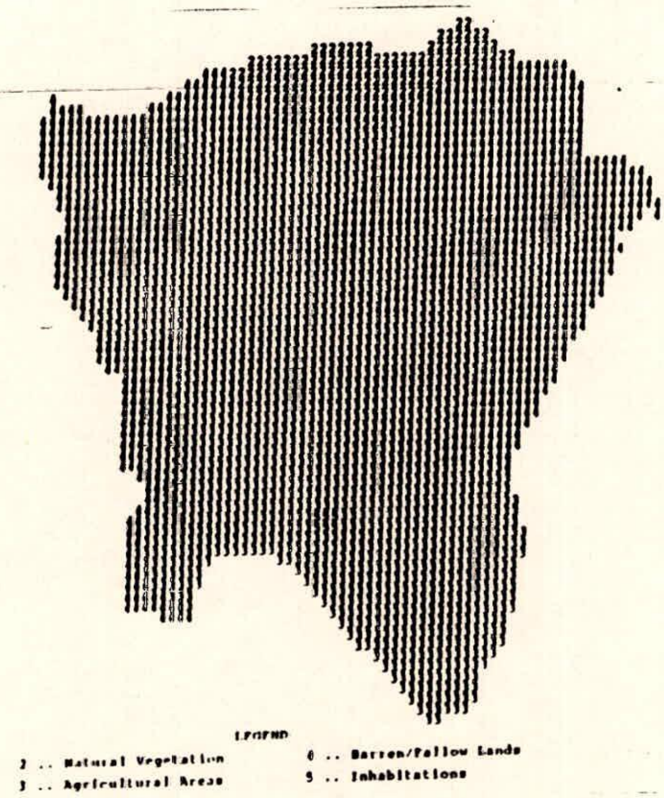
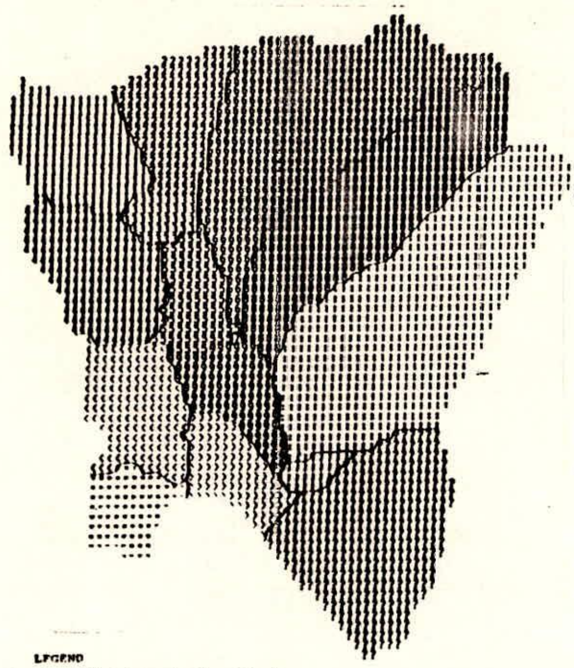


Fig. 8 Land Cover features of the Study Area
From the satellite Data



LEGEND

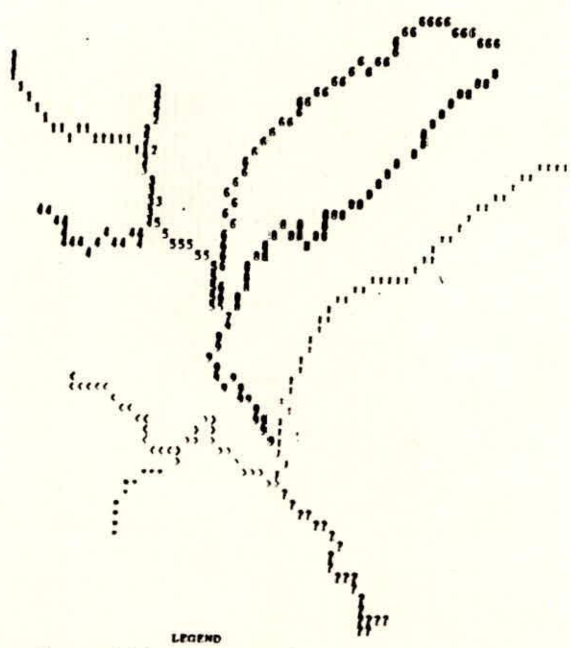
1 to 9 .. Sub-Catchments No. 1 to 9

, .. Sub-Catchment No. 10   • .. Sub-Catchment No. 13

; .. Sub-Catchment No. 11   > .. Sub-Catchment No. 14

< .. Sub-Catchment No. 12   ? .. Sub-Catchment No. 15

Fig. 9 Data Base of Sub-catchments



LEGEND

1 to 9 .. Streams of Sub-Catchments No. 1 to 9

, .. Stream of Sub-Catchment No. 10   • .. Stream ofSub-Catchment No. 13

; .. Stream of Sub-Catchment No. 11   > .. Stream ofSub-Catchment No. 14

< .. Stream of Sub-Catchment No. 12   ? .. Stream ofSub-Catchment No. 15

Fig. 10

Feature	C-Factor *
Natural vegetation	0.2
Agricultural areas	0.5
Predominently Agriculture with Barren/Fallow land/ Inhabitations	0.4

* based on values listed for different types of landcover in (18).

3.3 Erosion Loss Estimation

The values of various factors in the USLE were read from the respective data bases and multiplied to obtain the soil loss for each cell in tonnes per hectare. The cell-wise soil loss values were added to obtain the sub-catchment-wise erosion. While the values of the rainfall factor (R), the soil erodibility factor (K), the landuse management practice factor (P) were the same for all the cells, the values of slope length, steepness factor and vegetative cover factor varied from sub-catchment to sub-catchment as shown in Table 1 below.

Table - 1

Sub-catchment No.	Area in Sq. Kms.	R	K	L	S	C	P	Erosion in Tonnes per ha.
1	1.050	247.96	0.26	2.30	0.35	0.20	1.00	25.643
2	0.896	"	"	2.29	0.35	0.20	"	25.532
3	0.250	"	"	2.19	0.18	0.40	"	25.114
4	1.158	"	"	2.08	0.26	0.20	"	17.227
5	0.544	"	"	2.02	0.18	0.50	"	28.956
6	2.938	"	"	2.35	0.26	0.20	"	19.463
7	0.006	"	"	1.71	0.18	0.50	"	24.512
8	2.246	"	"	2.24	0.26	0.20	"	18.552
9	0.653	"	"	2.18	0.18	0.50	"	31.250
10	3.699	"	"	2.22	0.26	0.40	"	36.773
11	0.154	"	"	1.73	0.18	0.50	"	24.799
12	0.934	"	"	2.10	0.18	0.40	"	24.082
13	0.538	"	"	2.10	0.18	0.40	"	24.082
14	0.634	"	"	2.20	0.18	0.50	"	31.536
15	2.106	"	"	2.20	0.18	0.50	"	31.536

Note: Universal Soil Loss Equation give Soil Loss in tons per acre.

3.4 Sediment Yield Estimation

The sediment reaching the outflow point of a catchment will be only a part of the material eroded from the catchment. The downstream dimunition of sediment discharge takes place due to a variety of reasons, such as, channel aggradation, decrease in the flow velocity due to wider waterways, etc. The change in the downstream movement of sediment, from the source to a selected measuring point, is expressed in terms of a delivery ratio 'D', defined as the ratio of the sediment yield, Y, at the measuring point to the total erosion, T, and is expressed in percentage. The 'D' value usually decreases with increasing drainage area in a basin that is relatively homogeneous with respect to soils, climate and topography (26). Fig. 11 shows the variation in 'D' with respect to the size of the drainage area based on field investigations data (26).

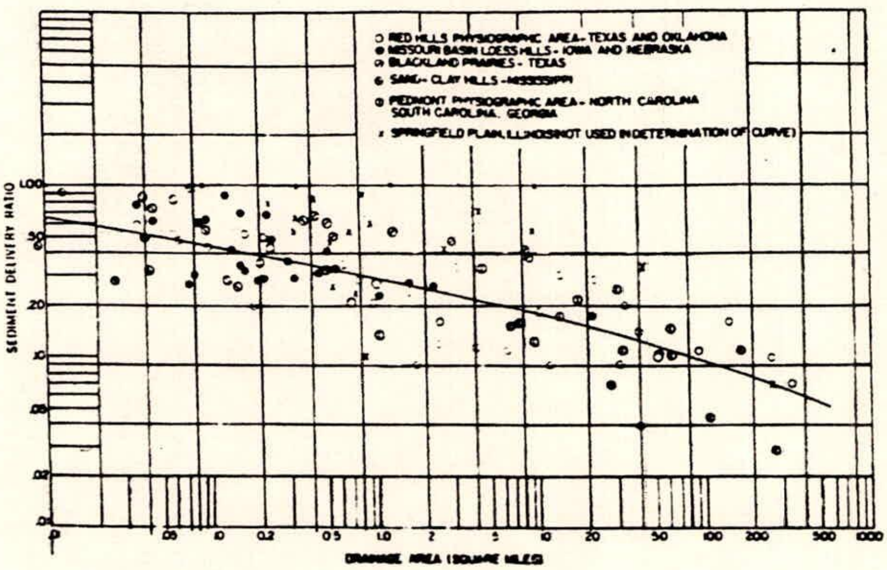


Fig. 11 Relationship Between Size of Drainage Basin And Sediment Delivery ratio (26)

The sediment yield for the sub-catchments were obtained as the product of the total erosion from a sub-catchment (Table 1) and the sediment delivery ratio 'D' read from Fig. 11 for the area of the sub-catchment. The resulting values for various sub-catchments are given in Table 2 below.

Table - 2

Sub-Catchment No.	Area in Sq.Kms.	Sediment Delivery Ratio	Total Erosion In Tonnes	Sediment Yield in Tonnes	Sediment Yield in Tonnes/ha
1	1.050	0.33	2692.52	888.53	8.46
2	0.896	0.35	2287.67	800.68	8.94
3	0.250	0.42	627.85	263.70	10.55
4	1.158	0.34	1994.89	678.26	5.86
5	0.544	0.38	1575.21	598.58	11.00
6	2.938	0.28	5718.23	1601.10	5.45
7	0.006	1.00	14.71	14.71	24.52
8	2.246	0.30	4166.78	1250.03	5.57
9	0.653	0.37	2040.63	755.03	11.56
10	3.699	0.26	13602.33	3536.61	9.56
11	0.154	0.48	381.91	183.32	11.90
12	0.934	0.35	2249.26	787.24	8.43
13	0.538	0.38	1295.61	492.33	9.15
14	0.634	0.37	1999.38	739.77	11.67
15	2.106	0.30	6641.48	1992.44	9.46
Total	17.806	0.394 (Avg.)	47288.44	14582.347	10.14 (Avg.)

The delivery of sediments from one location to a more distant location (eg. From a field, across several other fields, to a stream), can be determined using the following relationship (27).

$$DR = \propto \left[\frac{1}{\sum_{j=1}^{m} m_j \frac{1}{S_j^{0.5}} \frac{L_i}{H_{cj}}} \right]^{\beta} \qquad \dots (5)$$

Where Dr = Delivery ratio

m = number of downslope fields

j = j^{th} field along the flow path

S = Slope gradient

H = Hydrologic coefficient

$\propto$ and β = Constants

The assumptions involved in the above are (a) physical characteristics of entrained sediments do not vary spatially (b) hydraulic effects of run-off entering a field-size area from up-slope areas are negligible (c) main stream system delivers all the sediment transported to it. The equation gives potential in-situ gross erosion and the constants $\propto$ and β needs to be determined from calibration for application purpose.

4.0 Discussion, Conclusion and Suggestions for Further Work

4.1 Discussions

The average value of the sediment yield from Table 2 is 10.14 tonnes/ha or 1014 tonnes/Sq.km. This value compares well with the value reported by Ionita Ichim (28) for the Carpathians region in Romania, where the average altitude ranges between 300-500m, and the annual precipitation is between 600 and 1200 mm and the landcover is mixed woodland. The present study area also has comparable characteristics, average altitude being 600 m, mean annual rainfall around 700 mm and the landcover of mixed type. Based on multivariate statistical analyses of the relationships between the sediment yield and different controlling factors (28 independent variables including the Strahler system of basin order), the relationship predicting the best results is reported as (28).

$$S_y = [-4493.45 + 5826.65n (-671.06n^2)] / n^2 \qquad \text{... (6)}$$

Where n = the Strahler system basin order.

The gross erosion estimated from the above equation for the Carpathian region is reported to be between 1000-1500 $t/km^2/yr$. The sediment yields of small drainage basins have been taken to represent the gross erosion.

For the whole study area of 17.806 Sq. Kms., the sediment delivery ratio from Fig. 11 is 0.19. The average sediment yield for this ratio is obtained as 5.046 tonnes/ha., less than half the average value obtained on sub-catchment basis. This is in close agreement with the well established trend in sediment yield values for large areas compared to small areas.

4.2 Conclusions

The methodology developed based on grid area analyses for soil erosion and sediment yield estimation constitute a major improvement to the conventional method of sourcing the data to point observations. In particular, use of satellite data enable taking into account the landcover detail not only on a cell to cell basis but also enable use of near real-time data, thereby making it possible to obtain the results seasonally also. The results show that the sediment yield is relatively higher from sub-catchments 3, 5, 7, 9, 11 and 14 which are all close to the main flow route of the Nayagaon Nulla (Fig. 11) and constitute the foot slope areas of the headwater region. Hence it may be surmised that the region immediately below the headwater areas play a greater role in the transfer of sediment into the main stream channel of the study area.

4.3. Suggestions for Further Work

The grid-area approach needs to be improved upon for taking into account both the diminution aspects of the eroded soil along the sediment flow route and the bed load component of the sediment reaching the reservoir.

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