Journal of Spatial Hydrology
Vol.3, No.2 Fall 2003

ASSESSMENT OF THE IMPACT OF MINING ON AGRICULTURAL LAND USING EROSION-DEPOSITION MODEL AND SPACE BORNE MULTISPECTRAL DATA

Sreenivas Kandrika[1] and R.S. Dwivedi[2]
Agriculture & Soils Group
National Remote Sensing Agency
(Department of Space, Govt. of India)
Balanagar, Hyderabad – 500 037, India

E-mail: 1 sreenivas_k@nrsa.gov.in, 2 dwivedi_rs@nrsa.gov.in

ABSTRACT

Since erosion of mine overburden and mine dump leads to its deposition down the slope in the catchment, an attempt was made to study the erosion-deposition pattern in a micro watershed in part of Goa state, south-western India using the erosion-deposition model proposed by Mitasova et al. (1996). Information on various parameters of the model, namely curve number, management factor, cover factor, slope, soil erodibility, etc. was derived from the Indian Remote Sensing satellite (IRS-IC) Linear Image Self Scanning sensor LISS-III and PAN-merged data in conjunction with the DEM, field check and topographic maps at 1:25,000 scale. While only 11.2% of the area has been found to be under the protective cover of forest, 36.31 per cent of the area is under the influence of open cast mining, and a sizeable area is under scrubs. The impact of mining in terms of deposition of material has been observed in an estimated 219 ha of land, of which the agriculture land constitutes only 10 ha. Methodology and results are discussed in detail.

1. INTRODUCTION

Degradation of forestland by way of mining leads to very serious environmental hazards. Mining, in general, and open cast mining in particular may lead to severe environmental degradation. Paradoxically, from an environmental point of view, coal mining is a major habitat transforming activity which has a number of detrimental environmental consequences, namely soil erosion, acid-mine drainage and increased sediment load as a result of abandoned and un-reclaimed mined lands (Parks *et al.,* 1987). Besides, considerable amount of solid waste piled in the form of huge overburden dumps, destruction and degradation of forest and agricultural lands, and discharge of effluents from mines into nearby water-bodies are some of the other associated problems that have adverse environmental impact. Continuous monitoring of these lands is, therefore, essential for their effective reclamation and management. However, reliable and timely information on the nature, extent, spatial distribution pattern and temporal behavior of degraded lands including land subject to mining, which is a pre-requisite for their reclamation and management, is generally not available.

Remote sensing by virtue of synoptic coverage at regular intervals, is quite useful in monitoring land disruption due to mining (Wier et al., 1973, Irons et al., 1980; Parks et al., 1987), detection of mine fires (Richards, 1983), mining revegetation and the monitoring of reclaimed lands (Legg, 1986), water pollution assessment (Repic et al., 1991), monitoring (Lathrop and Lillesand, 1986; Lillesand et al., 1987), and detection of land subsidence (Mechaffie and Seargent, 1985; Volk et al., 1990). Besides, spaceborne spectral measurements also enable predicting the extent of forest cover due to mining (Murthy et al., 1997)

The present study was, therefore, taken up (i) to assess the feasibility of delineating the extent of open cast mining and over burden material, and (ii) to assess the impact of mining on agricultural in part of Goa state, south-western India, using PAN and LISS-III data.

3. STUDY AREA

Covering a geographical area of 1,698 ha, the test site is bound by geo-coordinates 15^o 29’ to 15^o 33’ N and 74^o 02’ to 74^o 06’ E and forms parts of Bicholim and Satari *talukas* (an administrative unit) of Goa state (Fig-1). Rolling to undulating uplands, valleys and flood plain comprise the broad physiographic units. Geologically, the test site comprises of rocks of Precambrian age including quartzite, quartz schist, meta-volcanics, conglomerate (tilloid), pink phyllite with lenticular bodies of banded magniferous and ferruginous quartzite. The mining reserves are prominently seen in the Bicholim and Satari talukas. Open cast iron ore mines, piles of over burden material and iron ore, scrubs, grasslands, mixed forests and agriculture lands are the major land use/land cover categories encountered in the test site. Owing to high rainfall and resultant luxuriant vegetation coupled with high temperature, weathering process has been quite active. Due to leaching of bases, the dominant soils have been the members of Plinthhumults with the association of Tropudalfs and Hapludalfs. Intrusion of Dystrochepts does occur within the rolling to gently undulating plains. The members of Udipsamments are confined to flood plains only (Govindarajan et al., 1974). The natural vegetation consists of dense forests of dry-deciduous to moist deciduous type. However, rolling to undulating plains support scrubs and grasses. The climate of the area is warm and tropical with an average temperature of 21^o C. The average annual rainfall of the order of 3714 mm and 3690 mm has been recorded at Satari and Bricholim, respectively which receives mostly from south- west monsoon.

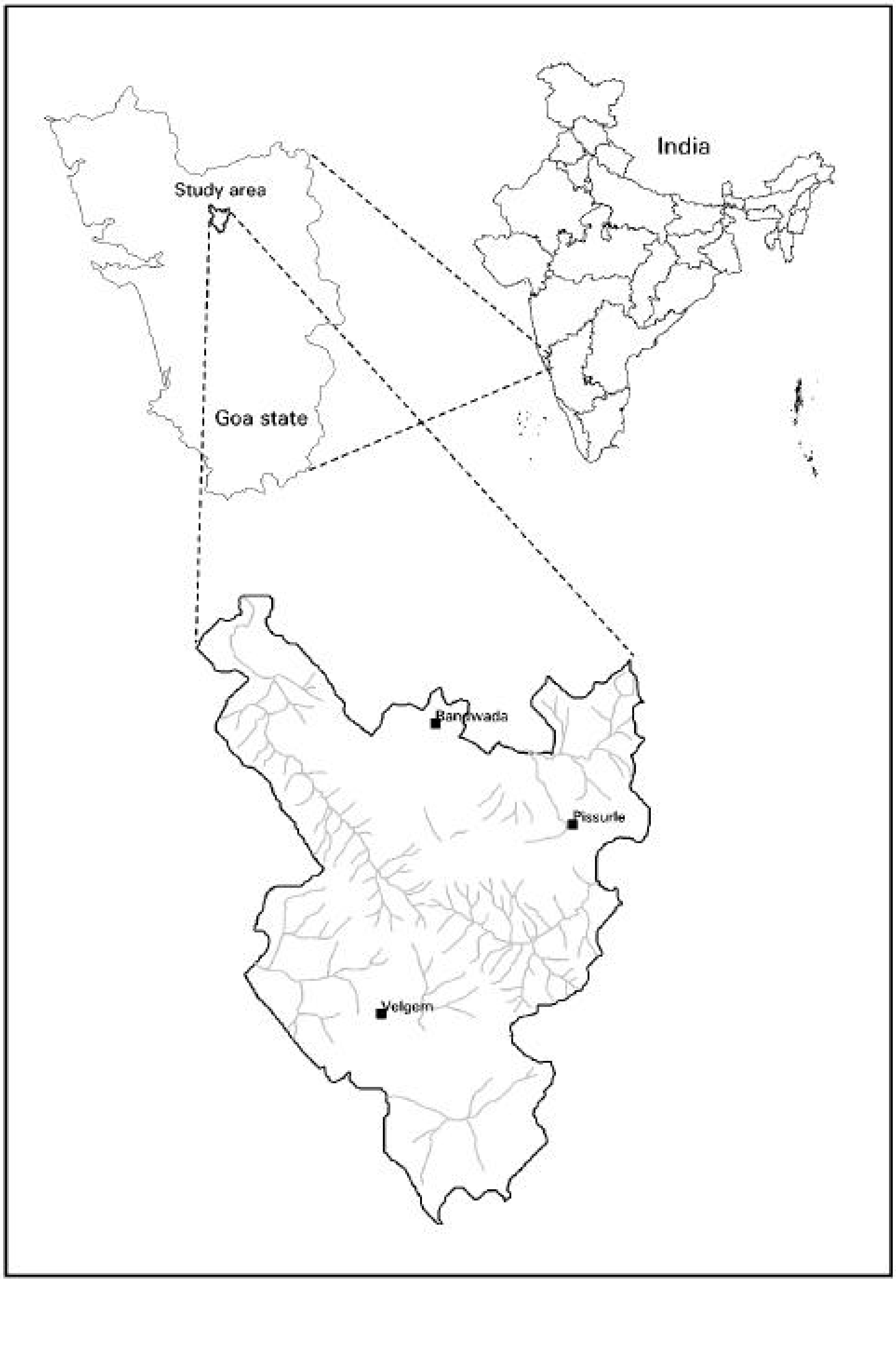

Fig-1. Location map of the study area.

4. DATABASE

The database used in this study consists of IRS-1C LISS-III and PAN data with path - row nos. 96 - 62, which were acquired on February 11, 1997. Besides, the Survey of India (SOI) topographic maps at 1:25,000 scale were referred during geo-referencing of raw satellite data and ground truth collection.

5. METHODOLOGY

The approach essentially involves database preparation, digital classification and a systematic on-the–screen visual interpretation of space-borne multispectral digital data. A flowchart portraying the methodology adopted in the present study is appended as Fig-2. Various steps involved in the analysis and/ interpretation are discussed hereunder:

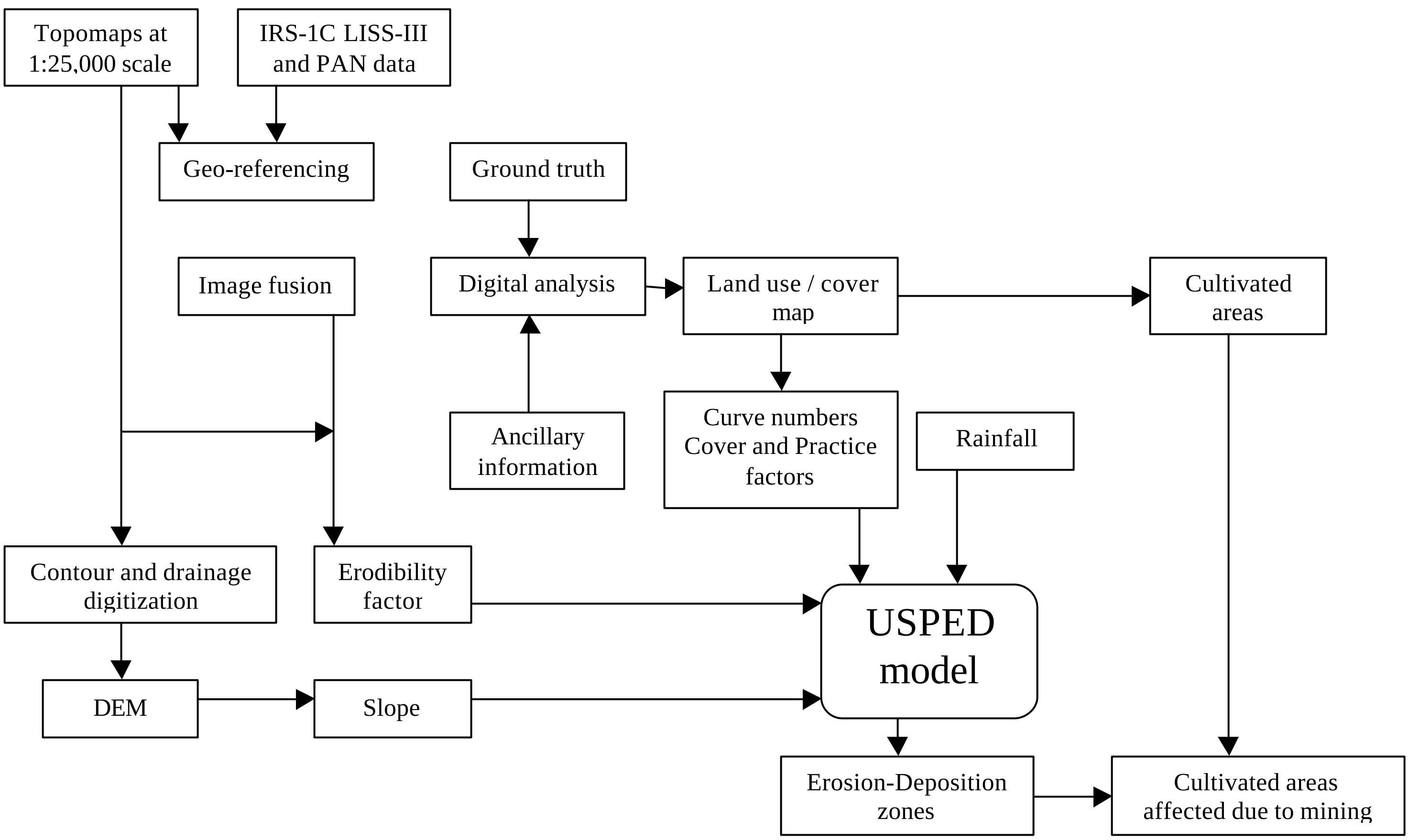

Fig-2. Flow chart of the methodology

5.1 *PREPARATION OF DATABASE*

Preparation of database involves geo-referencing and fusion of multi-spectral and panchromatic digital data. Details of various steps involved are given hereunder:

5.1.1 Geo-referencing

The IRS-1C PAN data were digitally co-registered to Survey of India topographic maps at 1:25,000 scale and resampled to 6m spatial resolution using first-order polynomial transform on a Silicon Graphics work station using ERDAS/ IMAGINE version 8.4 software. The digital data, thus generated, was used as a reference for geo-referencing IRC-1C LISS-III multispectral data, which was also resampled to 6m spatial resolution following the procedure adopted for PAN digital data.

5.1.2. Data Fusion

Data fusion is one of the important steps in bringing out the spatial information available in PAN data and spectral details with the multi-spectral data. As mentioned earlier, the LISS-III and PAN data were resampled to 6m spatial resolution and were fused using principle component data fusion technique provided in the ERDAS/IMAGINE 8.4 software. The algorithm, initially, converts the raw satellite data into principle components. Subsequently the first component was replaced with the high-resolution panchromatic data and an inverse principle component transform was performed to get red, green and blue components.

5.2. PRELIMINARY *DIGITAL ANALYSIS*

For objective assessment of the lands affected by mining activities, quantification of sediment from the mining sites is a pre-requisite. To predict the sediment detachment, information on the land cover, slope, management practices, soil erodibility is essential. Hence, preliminary interpretation of satellite digital data was carried out to delineate various land use / land cover categories in conjunction with the Survey of India (SOI) topographic maps. Simultaneously, preliminary interpretation was also done for mapping soil properties by exploiting the inherent relationship between lithology, physiography and land cover. The iron rich over burden material dumps are clearly seen in the image as various shades of green and yellow colours depending on iron and gravel contents. Mining areas could be broadly delineated on the LISS-III data by their characteristic spectral response pattern. However, after merging the LISS-III with PAN data, various stages of mining and other associated disturbed areas could also be discerned.

5.3. *GROUND TRUTH COLLECTION*

Ground truth mission was subsequently planned to establish the relationship between image elements, namely color, texture, shape, size, shadow, pattern, association, etc. and various features associated with the mining in random sample strips. Initially, a reconnaissance traverse of the area was made to assess the trafficability and to precisely locate sample areas. Intensive field observations were then made in sample areas on various land use / land cover categories and soil properties. Precise location of the sampling sites was recorded with the help of a Global Positioning System (GPS) receiver model Magellan ProMark-X. Soil samples were collected from these sites and analyzed for physical and chemical properties. Additionally, for drawing comparison, a few observations were also made on sediment concentration of the runoff from both undisturbed as well as from areas affected by mining.

5.4. *FINAL DIGITAL ANALYSIS*

Various categories of land use / land cover verified during ground truth collection phase were marked in the geometrically corrected digital satellite data as training sets on a Silicon Graphics workstation using ERDAS/ IMAGINE version 8.4 software. The spectral response patterns of various land use / cover categories were generated using signature editor module. Subsequently, the separability analysis of various classes in terms of Transformed Divergence (TD) was carried out. Further refinement in the training sets was made to improve the separability of various land use / cover categories. Entire image was then classified using Gaussian maximum likelihood per-pixel classifier.

5.5. *GENERATION OF DEM*

Generation of Digital Elevation Model (DEM) is essential, amongst other aspects, to study the topographically susceptible areas for erosion and deposition, and also to derive information on the slope and aspect of the terrain. Initially, the Survey of India (SOI) topographic maps at 1:25,000 scale were placed on A0 size Calcomp digitizer and geo-referenced. Subsequently, the contour information provided in the topographic map was digitized as line features and spot heights as point features using ARC/INFO 7.3.1 software. The elevation values of each of the contour line was stored as attribute information and corrected for topological errors. Besides, the drainage network was digitized as line coverage and, like contour coverage, was also corrected for topological errors and arc directions. The arc coverages (contour and drainage), thus generated, were used for generating DEM using *topogrid* command. Since the DEM will have sinks that are generated during the DEM creation, initially, they are labelled followed by their filling. Water bodies and silt trapping ponds were digitized and the corresponding elevation values.

5.6. *MAP FINALIZATION*

The spatial distribution of soil properties delineated during preliminary visual interpretation has been modified in the light of ground truth and soil chemical analysis data by displaying the PAN-merged LISS-III data on the colour monitor of the Silicon Graphics workstation using ERDAS IMAGINE version 8.4 software. And the vector coverage was generated and its topology built. The physical and chemical properties of soils were attached as attribute information in a Polygon Attribute Table (PAT).

5.7. *USPED MODEL*

The Unit Stream Power Erosion-Deposition (USPED) model developed by Mitasova et al. (1996) was used in the present study to predict the erosion-deposition zones. The model is simple and predicts the spatial distribution of erosion / deposition as the divergence of sediment flow under steady state conditions. The outline of model is as follows:

$$D = \text{div } q = Kt\,[\text{grad } h] * S \sin(b) - h\,[kp + kt] \qquad \text{Equation (1)}$$

where,

D = Net rate of erosion / deposition

K = Transportability of sediment

h = water depth estimated from upslope area

S = unit vector in steepest slope direction

b = Slope in degrees

kp = terrain curvature in the direction of steepest slope

kt = curvature tangential to a contour line projected to normal plane.

Further, to predict the transport capacity of the sediment it uses the following equation:

$$T = R\ .\ K.\ C.\ P.\ A\ (\sin b)^n \qquad \text{Equation (2)}$$

where,

T = Transport capacity of the sediment

$R = i^{m}$ Equation (3)

where, i = intensity of the rainfall (mm/hr) and

m = an exponent

K = MUSLE soil erodibility value C = MUSLE cover factor

P = MUSLE practice factor A = Area of the grid cell

b = Slope in degrees n = an exponent

The exponents m and n values are 1.6 and 1.3, respectively for a rill erosion case and m = n = 1 for a sheet erosion case. Since most of the sediment will be contributed by mining material heaps where rill erosion is predominant, in the present study the exponents m = 1.6 and n = 1.3 were used. Since, the rainfall intensity values are difficult to get in this area for a particular event, we have replaced the energy component i.e., rainfall intensity with runoff component of Modified Universal Soil Loss Equation (MUSLE). To compute the runoff Curve Number (CN) method was used. Thus the equation could rewrite as:

$$T = 11.8 \cdot (Q \cdot Q_p)^{0.56} \cdot K \cdot C \cdot P \cdot A^m (\sin b)^n \qquad \text{Equation (4)}$$

where,

Q = runoff of an event for the cell under consideration (m^3)

Q_p = Peak rate of runoff (m^3/sec) as defined in AGNPS model

The net erosion / deposition of sediment can be computed as:

$$D = d(T * \cos \alpha) / dx + d(T * \sin \alpha) / dy \qquad \text{Equation (5)}$$

where,

α = Aspect of the terrain (degrees)

For the purpose of implementing the model in ARC/INFO GRID environment, source code provided by Mitasova and Mitas (1999) has been used after necessary modifications.

5.7. GENERATION OF INPUT GRIDS

The computation of erosion - deposition zones involves generation of various input grids. One of them is curve number grid, which is required for computing runoff. Besides, soil erodibility, cover, management and slope are also required for computing the detachment. The methodology adopted for generating various input grids is given hereunder:

5.7.1. Curve Number Grid (CN)

The spatial information on hydrological grouping of soils and land use/land cover is a pre-requisite for generating cell-by-cell curve numbers. Hence, the land use/land cover and soil coverages were converted into grid using *polygrid* command. The conditional rules were then framed using *if…then* and *con* commands to derive the curve number grid.

5.7.2. Soil Erodibility Grid (K)

Though the soil erodibility was determined though RUSLE equation. Information on the each soil polygon viz., sand, silt, clay, organic matter content, structure, etc. was stored in the form of attributes in Polygon Attribute Table (PAT). To derive the soil erodibility, the K-factor prediction equation, as defined in RUSLE manual, was run on the attribute data of soil coverage. The resultant K-factor was stored as another attribute. Using *polygrid* command and K-factor as variable, a K-factor grid was then generated.

5.7.3. Cover Factor Grid (C)

In order to generate cover factor grid, the land use/land cover image was initially converted into grid. Using the RUSLE parameter computation package, the crop cover factor was computed for various land use / land cover categories. For land cover classes like forests, scrubs and grasslands, a single cover parameter was used, as there is no significant change in the surface cover during the period of rainfall-runoff events. The land cover categories like mine dumps and the features associated with the mining were given a C-factor value of 1.0, since there is hardly any vegetation cover.

5.7.4. Management Practice Grid (P)

The management practices were assessed from the ground truth information and land use / land cover grid, and a grid depicting the management practices (M-grid) was generated. Terracing is a common practice followed in the mining area. For other areas, the management practice factor is set to 1.0. Then, rules were framed for assigning the management practice factor values using M-grid along with the slope grid to finally derive the practice factor grid (P-grid).

5.8. EROSION - DEPOSITION ZONES

The parameter grids, thus generated, were used to predict the sediment transport capacity, which was then used to predict the erosion – deposition zones of an event. For the purpose of predicting runoff, the maximum rainfall recorded in the area during the past 30 years has been used. Since the slope and its tangential directions play an important role in deciding the erosion / deposition at particular cell, it was considered as appropriate model available to predict erosion / deposition process. Since the objective of the study is to assess the impact of mining on agricultural lands, the erosion from the mining areas only was computed while setting the detachment from other areas to zero, such that the deposition zones show only areas where the deposition from over burden material is taking place. Subsequently, the erosion - deposition index was arbitrarily sliced into various regions for better appreciation of the magnitude of topographic influence on erosion - deposition process. The erosion - deposition grid was overlaid onto land use / land cover grid to identify the cultivated areas where deposition of eroded material from the mining areas is taking place. For validation of the results, a ground truth campaign was subsequently launched. Runoff samples from various pour points were also simultaneously collected for a single rainfall event to objectively compare the sediment concentration in the runoff vis-à-vis land use / cover pattern of the catchment of a pour point. It would have been better; in fact, if a systematic runoff and sediment measurements were to be made after establishing gauging stations, which is a cost-prohibitive apart from involving a lot of logistics.

6. RESULTS

The results of the study have been discussed in the following two sections. The first section deals with the land use/ land cover of the area, the second with the erosion-deposition aspects.

6.1. DELINEATION OF FEATURES ASSOCIATED WITH MINING

The satellite images of the area along with the land use / land cover map derived therefrom are appended as Fig-3a and b, respectively. Mining areas are clearly separable on the image (Fig-3a) since the over burden material rich in iron content lends a characteristic green color in the standard false colour composite (FCC) image due to high reflectance in the red band. Added to this, the over burden material also contains a lot of gravels which act as diffuse reflector, increasing thereby the over all reflectance of the target. On the other hand, the iron ore, which is a concentrate of iron, is black in color and fine in texture. Hence it appears as dark patches of irregular-shaped feature on the image. Furthermore, it is also evident from the map that the mining areas and their associated features like dumps, ores, etc. do not have adequate vegetation cover to protect the soil from water erosion. The fact is supported by the absence of signature of vegetation cover (different shades of red colour) in these areas in satellite image. In addition other land use/ land cover categories, namely forest land, scrubs, grass land, fallow land and water bodies could also be delineated.

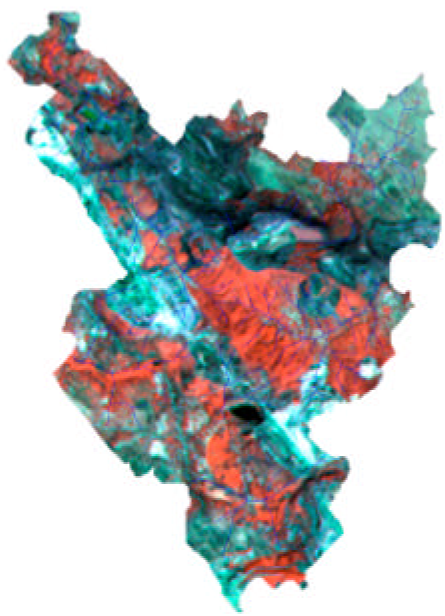

Fig-3a. IRS-1C LISS-III and PAN-fused data.

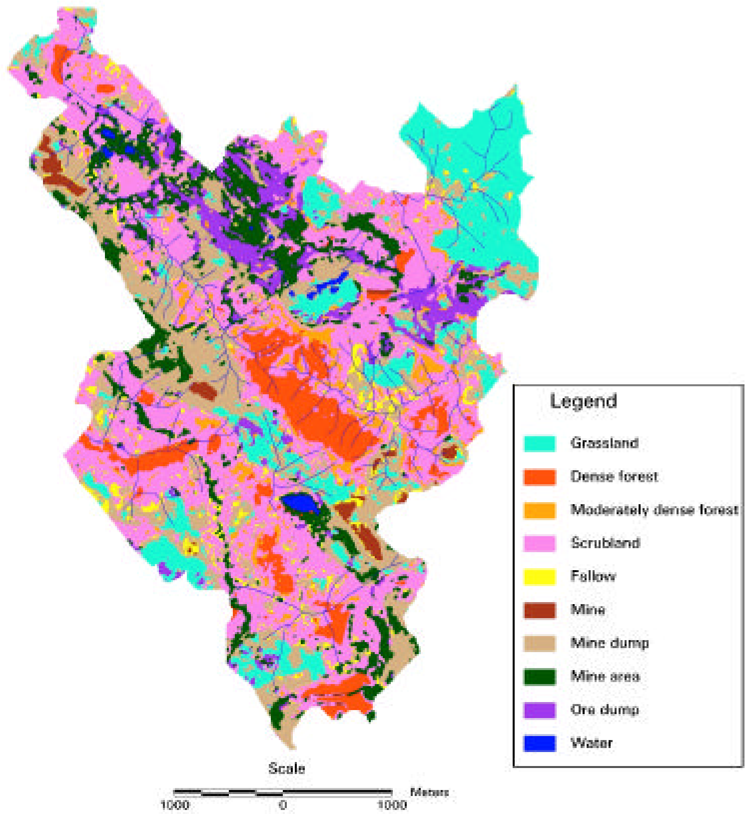

Fig-3b. Land use / cover map.

The spatial extent of various land use / land cover categories is presented in the Table-1. A close look at the table reveals that the area is dominated by mining-related features (618ha) followed by scrubs (578ha). An estimated 36.31% of geographical area is under the influence of open cast mining. Contrastingly, the forest cover, which protects the land from erosion by water, constitutes only 11.2% of the area. Of this, 7.1% area is under dense forest and 4.1% under moderately dense forest. Croplands occupy only 3.3% of the test area.

6.2. EROSION - DEPOSITION ZONES

The IRS-1C LISS-III and PAN-merged data along with the maps of various factors contributing to erosion and deposition processes, namely land use/land cover map, map showing hydrological groups, soil erodibility, cover factor, management factor, slope and the spatial distribution of erosion-deposition pattern are appended as Fig 3b, 4a, 4b, 5a, 5b, 6a and 6b, respectively. The areal extent of various erosion-deposition zones is appended as Table-2. In Table-2, the positive values indicate the areas experiencing erosion while negative values the deposition zones. As could be seen from the Table, an estimated 219ha of total area is subject to deposition of material from the mining areas; out of which, only 10ha of land is under agriculture. In the subsequent ground truth mission that was launched to validate the results, it was observed that the depositional areas near the foothill zones are matching well with the predicted ones. However, in the cultivated areas, the deposition of sediments from mining areas had been taking place earlier. Due to adoption of appropriate soil conservation measures, the deposition of sediments has been considerably reduced.

The information collected from farmers reveals that the acidity in the cultivated areas has been considerably increased (pH lowered) in areas where deposition of sediment from mining took place with an attendant reduction in the paddy yield. Further, the subtle variations in the topography which plays a key role in erosion – deposition process could not be derived from the DEM that was generated by interpolation of contours (10m interval) from the 1:25,000 scale topographic maps. In this endeavor, aerial photographs with stereo coverage or high spatial resolution satellite data with stereo capability may provide possible solutions.

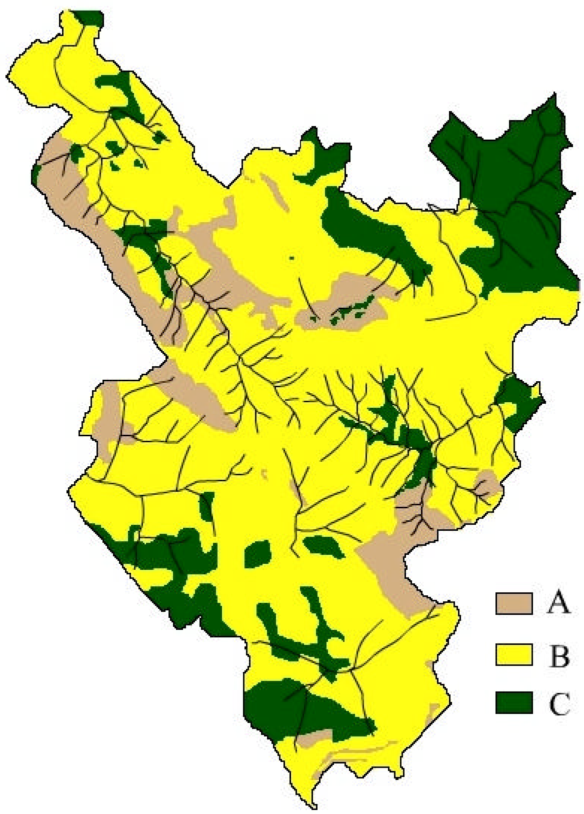

Fig-4a. Hydrological soil groups.

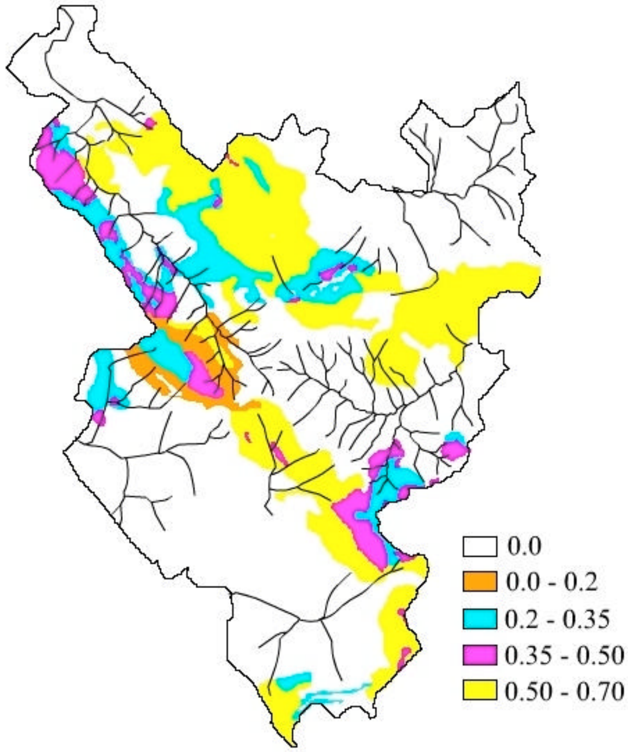

Fig-4b. Soil erodibility map.

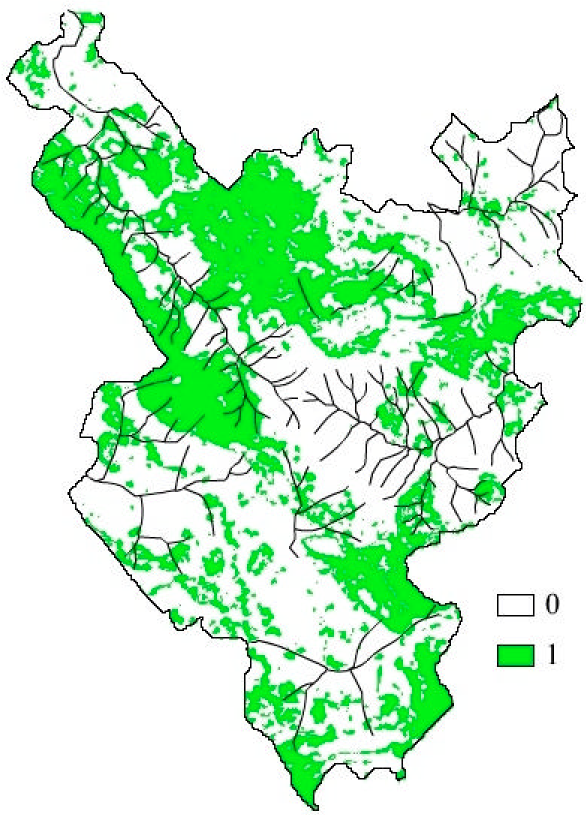

Fig-5a. Cover factor map.

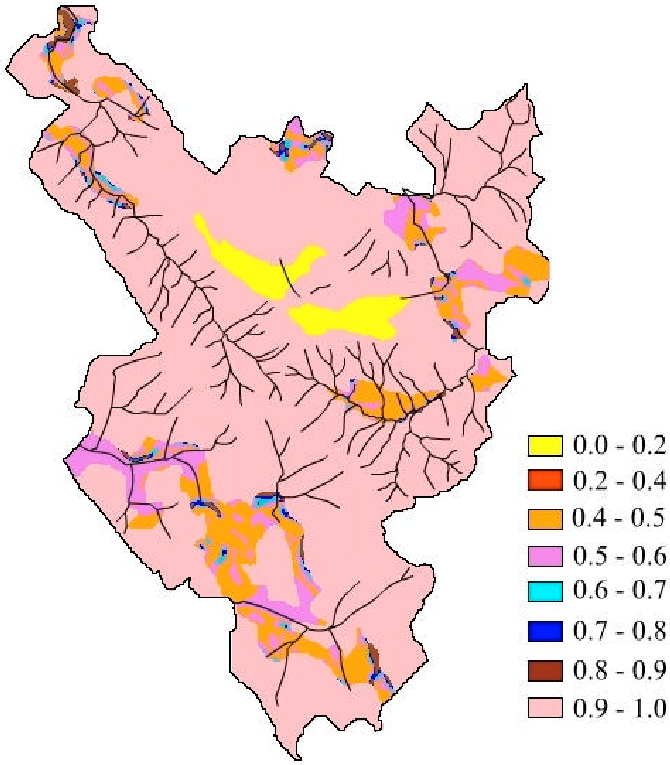

Fig-5b. Management factor map.

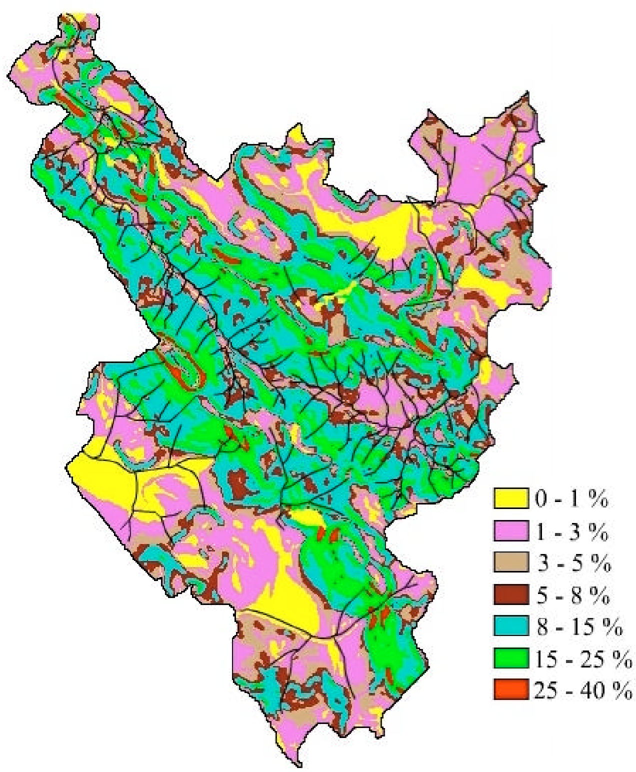

Fig-6a. Slope map.

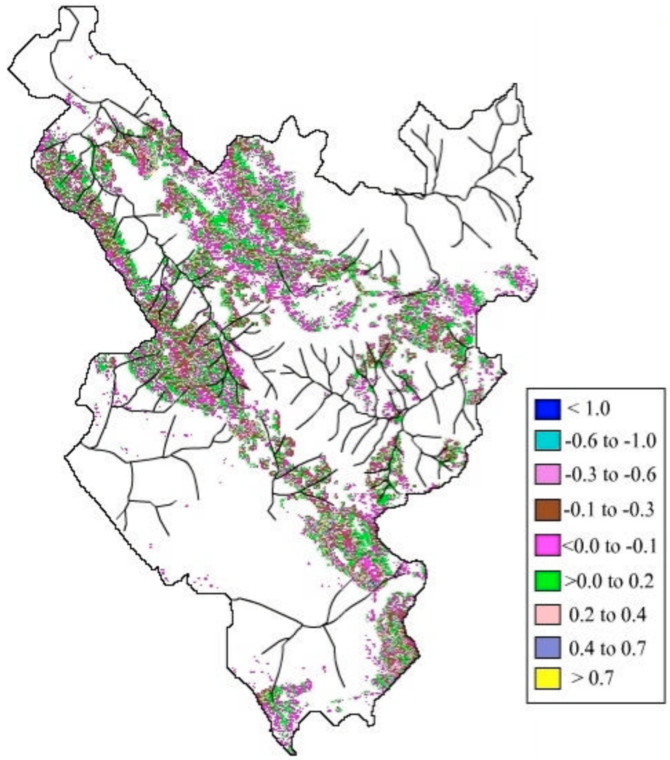

Fig-6b. Erosion – deposition map

The results of sediment concentration are shown in Table-3. It is amply clear from the observations that the sediment concentration from mining areas is very high as compared to undisturbed areas, which are protected well with the natural vegetation cover. Further, an observation from the forest watershed (G6) signifies that the sediment concentration could be very low if a good cover is established. For instance, the sediment concentration of 5.98 g/l has been observed in mining areas against 0.01 g/l in case of full forest cover (Table-3) pointing thereby to the role of surface cover in arresting the soil loss. In addition, an increase in the sediment concentration in the runoff water has also been observed with an increase in the over burden material from mining areas in the catchment. The soil separate analysis of sediments from mining areas shows that the coarse sand and gravel constitute the major component. In contrast, the areas where conservation practices have been adopted, only finer material (clay and fine silt) has been observed in the runoff. Since the overburden material is composed mainly of coarse sediments, conservation practices that trap the sediment are necessary to reduce their loading into runoff, preventing thereby the siltation of water bodies and streamlets.

7. CONCLUSIONS

It is evident from the foregoing that mining leads not only to pollution of surface and ground water but also accelerates erosion by water which, in turn, results in the deposition of the mining wastes in agricultural fields which may affect the growth and yield of agricultural crops. In the present study a spatial erosion-deposition model viz., USPED model has been used to assess the extent of agricultural land affected by open cast mining. Satellite multi-spectral data enabled deriving information on soils and land use/cover of the area. Whereas, soil erodibility was derived from soil map, curve number and cover factor from land use / cover map. The slope information has been derived from DEM generated using SOI topomaps. These parameters were then used to run the USPED model to retrieve erosion-deposition zones in a GIS domain. The information on area under agriculture as derived from land use / cover map and was integrated with erosion-deposition zones to demarcate the area affected by opencast ore and overburden dumps. The limitation of the current model is that it cannot account for sediment deposition under erosion conservation scenario, for which a cell-by-cell sediment routing models need to be considered. The DEM generated by interpolation of contours does not seem to portray true field conditions resulting thereby in inaccuracies in the prediction of deposition zones especially in plain areas and valley bottoms due to interpolation errors. Hence, there is a need to look for better DEM generation procedures, which can depict subtle variations in topography.

ACKNOWLEDGEMENTS

The authors wish to place on record their sincere thanks to Dr. R. R. Navalgund, Director, and Prof. S. K. Bhan, Associate Director, and Dr A. K. Bhattacharya, Deputy Director (Remote Sensing and GIS), National Remote Sensing Agency, Hyderabad for providing financial support and constant encouragement during the course of investigation. Our thanks are also due to Dr. L. Venkataratnam, Group Director, (Agriculture and Soils) for evincing keen interest in the study. Thanks are also due to National Institute of Oceanography (NIO), Goa for providing laboratory facility for analysis of runoff samples. We are also grateful to Dr. K.V. Ramana, Mr. S. Senthil Kumar and to Mrs. G. Sujatha for their technical support during the course of investigation.

REFERENCES

Govindarajan, S. V., Murthy, R. S., Jain, S.P., Raghumohan, N. G., and Venkataraman, M. (1974) A survey of natural resources of Goa with particular reference to soils and land classification for agricultural development, ICAR Technical Bulletin No. 49, Indian Council of Agricultural Research, New Delhi.

Irons, J. R., Lachhowski, H., and Peterson, C. (1980) Remote sensing of surface mines: A comparative study of sensor systems, Proceedings of the 14^{th} International Symposium on Remote Sensing of the Environment. San Jose, Costa Rica, April, 1980, Ann Arbor Michigan: Environmental Research Institute of Michigan, pp : 1041-1053.

Lathrop, R. G., and Lillesand, T. M. (1986) Utility of Thematic Mapper data to assess water quality in Southern Green Bay and West-Central Lake, Michigan, Photogrammetric Engineering and Remote Sensing, 52 : 671-680.

Legg, C. A. (1986) Monitoring of open cast coal mining and reclamation works in the United Kingdom using MSS and TM imagery, Proceedings of the 20th International Symposium on Remote Sensing of the Environment, San Jose, Costa Rica, April, 1990, (Ann Arbor Michigan: Environmental Research Institute of Michigan), 2, pp : 931-941.

Lillesand, T. M., Lathrop, R. G., and Vandre Castle, J. R. (1987) Towards an integrated system for satellite remote sensing of water quality in the Great Lakes, Proceedings of the Falls ASPRS Meeting, Reno N. V. (Virginia: American Society for Photogrammetry and Remote Sensing.), pp : 342-347.

Mechaffie, P. H., and Seargent, R. E. (1985) Detection and delineation of mine related subsidence in Western Kentucky coalfields, ASCM-ASPRS Fall Meet Proceedings, Indianapolis, 8-13th September, 1985 (Falls Church Virginia: American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping), pp : 538-554.

Mitasova, H., Hofierka, J., Zlocha, M., and Iverson, L.R. (1996) Modelling topographic potential for erosion and deposition using GIS. International Journal of Geographic Information Systems, 10(5) : 629-641.

Mitasova, H. and Mitas, L., 1999, Erosion/deposition modeling with USPED using GIS. http://www2.gis.uiuc.edu:2280/modviz/erosion/usped.html.

Murthy, M.S.R., Subramanian, S.K. and Dutt, C.B.S. (1997) Environmental impact analysis of bauxite mining, Eastern Ghats, Andhra Pradesh using remote sensing data, NNRMS Bulletin, Dept. of Space, Govt. of India, Bangalore, (B) 21: 30-35.

Parks, N. F., Peterson, G. W., and Baumer, G. M. (1987) High resolution remote sensing of spatially and spectrally complex coal surface mines of Central Pennsylvania: A comparison between SPOT, MSS and Landsat-TM, Photogrammetric Engineering and Remote Sensing, 53 : 415- 420.

Repic, R. L., Lee, J. K., and Mausel, P. W. (1991) An analysis of selected water parameters in surface coal mines using multispectral videography, Photogrammetric Engineering and Remote Sensing, 57 : 1589-1596.

Richards, W. Jr. (1983) Geological applications, Manual of Remote Sensing, R. N. Colwell (ed.) Falls Church Virginia: American Society of Photogrammetry and Remote Sensing.

Volk, P., Hayden, R., and Saradeth, S. (1990) Landsat and SPOT data - important tools for environmental assessment and hydrogeological applications, Proceedings of the Conference on Remote Sensing: An operational Technology for Mining and Petroleum Industries, London, 29-31 October, 1990.

Wier, C. W., Wobber, F. J., Orville, R. R., and Amato, R. V. (1973) Fracture mapping and strip mine inventory in the mid-west by using ERTS-1 imagery, Proceedings of the Symposium on Significant Results Obtained from the EARTH Resources Technology Satellite-1, Maryland, U.S.A., 5-9 March, 1973 (Washington, D.C.: National Aeronautics and Space Administration), pp : 553-560.