Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes (Proceedings of a symposium held at Vienna, July 1998). IAHS Publ. no. 249, 1998.

A site-specific systems-approach model for soil erosion and silt yield studies for hilly watershed management

J. ADINARAYANA, K. GOPAL RAO*, N. RAMA KRISHNA, P. VENKATACHALAM & J. K. SURI

Centre of Studies in Resources Engineering, Indian Institute of Technology - Bombay, Powai, Mumbai 400076, India

Abstract Erosion causing and related watershed characteristics, generated from multi-source data (remotely-sensed, map-based and ground-based systems), were input to a raster-based Geographical Information Systems (GIS) after having been geometrically co-registered to a standard grid (pixel). A set of knowledge-based rules, for assessing the soil erosion of the heterogeneous hilly watershed, were formulated from the knowledge of the multidisciplinary resource-experts and the knowledge of the *local* watershed characteristics, in addition to the field observations. This systems-approach model, which is hopefully fast, cost-effective and unaffected by individual bias, helped to infer the erosion intensity units that are most likely to occur at any given pixel in the system. Finally, the watershed was grouped into four different erosion intensity units namely: very severe, severe, moderate to severe and slight to moderate. A new integrated approach to identify priority/critical sub-watersheds by the Sediment Yield Index (SYI) model of the All India Soil and Land Use Survey (AIS&LUS, 1991), grouped the watershed into very high, high, medium and low priority sub-watershed classes. The significant variation in SYI values calls for conservation planning in cases of very high and high priority classes. A treatment-oriented land-use planning scheme using GIS, was formulated and suggested bio-engineering measures to reduce soil erosion processes further. The soil erosion information system thus generated, identifies the targeted problem areas for watershed conservation planning and for sustainable development of the hilly watershed.

INTRODUCTION

Soil erosion by water is the result of the interplay between watershed environmental factors such as soil, topography, drainage, rainfall and land-use pattern, data upon which are available from different sources/systems. Additional information through experience and knowledge of the multi-disciplinary experts also may be used for avoiding individual bias in assessing the soil erosion pattern of the area under interest. Hence, it is important to study the soil erosion by a systems-approach, analysing these multi-source watershed characteristics with multi-disciplinary expertise in an integrated manner. Watershed management programmes, in terms of conservation planning over a large watershed, must identify the subsets of hydrological units that are contributing most sediment load in the watershed. It is these priority or critical hydrological units (or sub-watersheds) that need preferential soil/water conservation measures to reduce maximum sediment loads in the watershed, particularly in arid/semiarid fragile environments.

* Department of Civil Engineering

The problem of soil erosion and its management is more serious with hilly heterogeneous watersheds which are subject to heavy rainfall. Geographical Information Systems (GIS) technology provides a means of introducing information and knowledge from different sources into the decision-making process, and help in handling and manipulating the multi-source data. A watershed is the base unit for the study, being a complete hydrological and topographical unit.

The aim of this paper is to describe a classification method for natural resources scientists that interactively integrates conventional techniques, remote sensing, GIS and the interpreter's expertise and knowledge. Our particular objective is to generate a GIS-assisted soil erosion map in an integrated manner avoiding any individual bias, and to suggest an integrated approach for identifying the critical/priority sub-watersheds on the basis of Sediment Yield Index (SYI) values (AIS&LUS, 1991).

The approach was tested in a drainage basin of about 100 km^2 in the typically semiarid and difficult terrain of the Western Ghats mountanous area (73°45'–73°55'E, 19°16'–19°23'N). The area has a basaltic landscape, and is located in the Western Plateau and Hill agro-climatic region of the Indian Peninsula. Increasing accumulations of sediments are being deposited in the drainage ditches, and ultimately in Yedgaon reservoir, a terminus of drainage for the watershed. The siltation is largely due to poor soil conservation practices, scantily distributed vegetation cover, steep slopes and an overall dry climate with erratic monsoon rainfall resulting in a high susceptibility to erosion. If erosion is not stopped, further increases in runoff will ultimately destroy the productive value of the land. Hence, a systems-approach for assessing the soil erosion of this heterogeneous hilly watershed is required for conservation planning.

DATA SOURCES

Keeping in view the integrated approach to be adopted, the following data were used:

- Remotely-sensed data: Landsat-TM and IRS-1A LISS II—digital (Computer Compatible Tapes—CCTs) and visual (False Colour Composites—FCC) products of monsoon (kharif) and post-monsoon (rabi) agriculture seasons.
- Survey of India (SOI) topographical maps at 1:250 000 and 1:50 000 scales.
- Available literature and maps on various themes.
- Meteorological data (rainfall, temperature, etc.).
- Ground survey information on soil and other terrain characteristics of the sample sites of the watershed.

DATABASE CONSTRUCTION

The GIS used was the PC-based, indigenously-developed package, called GRAM (Geo-Referenced Area Management). The data sources were integrated in the GIS in grid-cell format. Digitisation, geo-referencing and rasterization were done in the input module. The output of this module was used as the base for an analysis module to integrate and process using logical combinations and knowledge-based rules. The erosion intensity map and the results were the output of the print module.

Each defined cell (pixel) has an exact location in space, related to the grid orientation and cell size and a list of assigned attributes. The information database was geometrically corrected, using a Survey of India (SOI) topographic map base and re-sampled to 30 m resolution (of Landsat-TM). A grid size of 515 × 492 pixels covered the whole watershed.

A GIS-assisted improved land-use classification system was adopted (Adinarayana & Rama Krishna, 1996) to overcome the inherent problems of the heterogeneous hilly watersheds: (a) discriminating various spectrally inseparable vegetation categories of natural vegetation and cropping systems; (b) mapping agricultural land-use pattern of this rural-based watershed; and (c) finding out the land-use/cover classes under the cloud and its shadow areas.

A collective approach, comprising satellite data from the Indian Remote Sensing Satellite (IRS) and topographic maps was used for physiographic soils mapping. The contours and height points were digitized from 1:50 000 SOI topographic maps (20 m interval) to generate the Digital Elevation Model (DEM) and the slope map with the help of the GRAM package. An isohyetal map was compiled manually from ten years of mean annual rainfall data from six meteorological stations available in and around the watershed. The drainage network was generated from the SOI topographic sheet (of 1975) and the high order river course systems were updated from Landsat-TM imagery (of 1989). The proximity analysis was done to establish the buffer zone along the drainage lines to demarcate the zones where erosion was likely to be important. The watershed was systematically divided into 33 sub-watersheds, which are smaller hydrological units and constitute individual tributaries of the lowest order, or a group of such tributaries. The area of each sub-watershed was planometrically computed and ranged from 1.4 to 7.0 km^2, which is considered to be a viable working size for conservation planning.

All the previously described thematic maps were digitized, rasterized and brought to a common co-ordinate system, which thus acted as database for GIS analysis to generate the derivative maps.

DATABASE ANALYSIS

Soil erosion assessment

Generation of integrated resources units Given that all the data layers are now spatially part of a common co-ordinate system, a number of useful combinations can be performed. The first step in this process is to create a basic unit by overlay analysis, and to create an Integrated Resources Unit (IRU). Each IRU comprises the watershed characteristics data on soil, slope, land use, rainfall distribution and drainage buffers for one grid cell. One IRU has been taken as the basic strategic unit for assessing the soil erosion. Since they exhibit strong uniformity, they can all be expected to respond similarly to given intensities of human use and management strategies. Each IRU descriptor was derived from watershed factors superimposed as layers in a GIS. Adjacent sets of IRU attributes were then separated.

Taking all the watershed environmental factors and their attributes into consideration, 270 IRU combinations should occur in the watershed, whereas only

228 IRU combinations appeared in the watershed and are considered in our overlay analysis.

Knowledge-based rules The link between the GIS database layers and the soil erosion intensity unit is provided by information-based rules. In the implementation of these rules, the multi-disciplinary expertise and knowledge of the local terrain parameters and field observations were taken into consideration, as well as the authors' expertise in soils, land-use planning, remote sensing and GIS. In the present study, the rules were expressed as the probability of an item of evidence occurring given a particular hypothesis. The rules are the most subjective aspect of the information-based system. They are heuristic, estimated from the informed opinion of the experts (Skidmore *et al.*, 1991).

The knowledge-based rules for each IRU and their probability of erosion risk factor has been worked out. Two contrasting examples are:

(a) If 5° slope
other drainage area
Typic chromusterts
< 1500 mm rainfall zone with thick forest
Then Class = slight to moderate erosion risk

(b) If > 18° slope
1–2 drainage orders
Typic ustorthents
> 1500 mm rainfall zone with open areas
Then Class = very severe erosion

Thus, these simple and useful logical combinations on a per pixel basis, enable mapping of the erosion intensity that is likely to occur at any given location, without any subjective bias. Finally, the soil erosion map was generated with four categories: slight to moderate, moderate to severe, severe, and very severe soil erosion intensity units.

An attempt has been made to use the multi-source data and GIS to estimate the soil loss using the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) for environmental conservation planning of this hilly watershed (Adinarayana & Gopal Rao, 1996). The soil loss was computed for each pixel as per the attributes and their values, and summed up for each sub-watershed independently making use of the sub-watershed map. The soil loss yield of all the sub-watersheds were added to obtain the total sediment yield of the watershed. The rate of soil loss estimated by the USLE method of the watershed was 28.11 t ha^{-1} $year^{-1}$ and closely matched the field observed value of 24.67 t ha^{-1} $year^{-1}$. The range of soil loss values (t ha^{-1} $year^{-1}$) for the erosion intensity categories was: slight to moderate (<20), moderate to severe (20-30), severe (30-50), and very severe (>50).

Silt yield studies

A new integrated priority delineation survey (Adinarayana, 1996), for taking up preferential soil/water conservation measures by the Sediment Yield Index (SYI) model of the All India Soil & Land Use Survey (AIS&LUS, 1991) carried out in the watershed, grouped the watershed into very high, high, medium and low priority classes. The methodology to prioritise the watersheds in the headwater region includes: (a) generation of information databases of soil, slope, drainage and density, land-use pattern and delineation of sub-watersheds; (b) generation of IRUs by overlay analysis; (c) assignment of weightage and delivery ratio values to IRUs based on combined effects of the environmental factors in terms of the erodability and erosivity potential of IRUs. Apparently, the areal extent of high and medium priority classes occupy about 80% of the watershed, which compares well with the occurrence of severe and moderate to severe erosion intensity unit categories by this systems-approach model.

Conservation planning

A major step in the conservation-oriented planning process is inventorying and classifying the watershed and then judging its capacity to support land-use on a sustained basis and also to avoid uses that degrade the land. A treatment-oriented land-use planning scheme, involving soil depth and slope steepness characteristics, was formulated through the use of multi-disciplinary knowledge-based rules and field checks in an integral manner through the use of GIS (Adinarayana & Rama Krishna, 1995). This scheme allocates potential land-use units, with proper soil and water conservation measures, to the high rainfall hilly watersheds. The priority sub-watershed delineation survey reveals significant variation in SYI values among the sub-watersheds. This suggests that planners should concentrate on these critical, or high and very high priority, sub-watersheds for conservation planning schemes such as the GIS-assisted scheme developed in the present study. If these appropriate biological engineering measures could be employed on the basis of priority, there would be less erosion. Consequently massive investments to control soil erosion, or worse, to rehabilitate the affected lands, could be reduced.

The soil erosion information system, assessment and management, thus

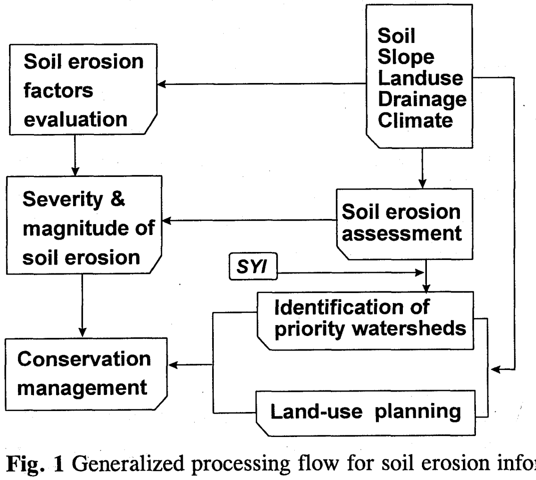

Fig. 1 Generalized processing flow for soil erosion information systems.

generated (Fig. 1), identifies the targeted problem areas for watershed conservation planning. The study also ensures the ability to monitor the dynamic changes of the watershed, particularly the land-use pattern, by remote sensing data with periodic intervals, and to re-define the conservation planning strategies on the basis of detected change. This systems-approach for hilly watersheds with variable rainfall regimes and severe land degradation problems is likely to provide more sustainable and cost-effective conservation management strategies.

The methodology attempted in the case study will be further tested in the other areas of hilly watershed ecosystem in the Western Ghat mountainous zone. Although this is an early airing of results obtained from the methodology described, the introduction of multi-disciplinary experts' informed opinion may provide an extension to the traditional methods of identifying soil erosion which should enable us to generate and/or evaluate different conservation scenarios. However, this systems-approach model is generally a site-specific and knowledge-based model generated for the Western Ghat zone which may differ from other ecosystems.

Acknowledgements This research project was financed by a research grant from the Department of Science and Technology, Government of India (through SERC Programme—ES/23/077/89). The authors wish to thank Prof. V.S. Chandrasekaran, Head of CSRE, for his constant encouragement and for providing facilities. Thanks are also due to my colleagues in CSRE for useful help, discussions and comments on this paper.

REFERENCES

Adinarayana, J. (1996) Prioritization of watersheds based on a silt yield index—an integrated approach. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. E. Walling & B. W. Webb) (Proc. Exeter Symp., July 1996), 549–554, IAHS Publ. no. 236.

Adinarayana, J. & Rama Krishna, N. (1995) An approach to land-use planning in a hilly watershed using GIS. *Land Degrad. & Rehabil.* **6**, 171–178.

Adinarayana, J. & Rama Krishna, N. (1996) Integration of multi-seasonal remotely-sensed images for improved landuse classification of a hilly watershed using Geographical Information Systems. *Int. J. Remote Sens.* **17**(9), 1679–1688.

Adinarayana, J. & Gopal Rao, K. (1996) Prioritisation of watersheds based soil erosion studies—A remote sensing approach. *Project Final Report, Centre of Studies in Resources Engineering, Indian Institute of Technology, Bombay, India.*

AIS&LUS (1991) *Methodology for Priority Delineation Survey.* All India Soil and Landuse Survey, Ministry of Agriculture, Government of India, New Delhi.

Skidmore, A. K., Ryan, P. J., Dawes, W., Short, D. & O'Loughlin, E. (1991) Use of expert system to map forest soils from a GIS. *Int. J. GIS* **5**(4), 431–445.

Wischmeier, W. H. & Smith D. D. (1978) Predicting rainfall erosion losses—a guide to conservation planning. *US Department of Agriculture Handbook no. 537.* Washington DC, USA.