A Systems-Approach Model for Conservation Planning of a Hilly Watershed

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1. Abstract

The watershed is the natural planning unit in modeling and monitoring of the effect of watershed management policies. To ensure optimum and sustained productivity through scientific planning, the watershed needs a decision-making information system that involves an appraisal of agro-ecological characteristics, resource limitations and potential of the watershed for resource development. This complete information helps in generating an information system for watershed management, a '*Watershed Management Information Systems (WATMIS)*'.

This paper describes an approach to develop WATMIS of a river basin chosen in the difficult, semiarid mountainous terrain of the Indian Peninsular region. The methodology includes compilation of various watershed resources from multi-source data (map, space and ground-based systems); development of Geographical Information Systems-based models for soil erosion evaluation and formulation of treatment-oriented land-use planning scheme with multi-disciplinary knowledge-based rules. A priority sub-watershed delineation survey carried out in the watershed indicates significant variation in sediment yield index values. This calls for conservation planning in cases of high and very high critical sub-watersheds. This systems-approach is related to the optimization of natural resources while minimizing the impact on the watershed environment. The paper envisages some future studies for watershed management strategies.

2. Introduction

Watersheds have assumed importance for preserving the ecological balance between natural resource development and conservation, particularly in the fragile and heterogeneous erosion-susceptible hilly ecosystems. The necessary information for resource planning on watershed basis includes the agro-ecological characteristics, resources constraints, and the potential of the watershed for sustainable development. This complete information helps in generating an information system for planning the watershed management programs of hilly terrain, what may be called a *"Watershed Management Information Systems (WATMIS)"* (1).

An attempt has been made to utilize remote sensing and Geographical Information Systems (GIS) for developing *WATMIS* of a hilly watershed. Remote Sensing is particularly useful in inaccessible areas. GIS is the most effective tool for integrating the data captured from different sources to produce a picture on which certain decisions can be based. The watershed is chosen as the fundamental unit in both the modeling and monitoring of the effects of watershed management policies.

The approach was tested in a drainage basin of about 100 km^2 in the difficult semiarid, mountainous terrain of the Western Ghats (73^o 45$'$ - 73^{o}55' E. 19^{o}16' - 19^{o}23' N). The watershed, which has a basaltic landscape, is located in the Western Plateau and Hill Agro-climatic Region of the Indian Peninsular.

Increasing accumulations of sediment are being deposited in the drainage ditches, and ultimately in the *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 overall dry climate with an erratic monsoon rainfall. Cultivation (rice systems) is being introduced in the canyons extending into the steeper mountainous area with inadequate soil conservation practices. If erosion is not stopped, further increases in runoff, and sheet and gully erosion on sloping ground will ultimately destroy the productive value of the land. Hence, a systems-approach for conservation planning is necessary for sustainable development of the watershed.

3. 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.

4. Database Construction

The GIS used was a PC-based, indigenously developed package, called *GRAM* (Geo-Referenced Area Management). The data sources were integrated in the GIS in grid-cell format. Digitizing, georeferencing 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 on logical combinations and knowledge-based rules. Utilitarian derivative maps were the output of the print module.

Each defined cell (pixel) has an exact location in space, determined by the grid orientation and cell size and a list of assigned attributes. The databases were geometrically corrected, using a SOI topographic map base, and resampled to 30-m resolution (of Landsat-TM). A grid size of 515 x 492 pixels covered the whole watershed.

4.1 Watershed Resources

Accurate information on the existing land-use pattern and its spatial distribution is a prerequisite for any watershed management program. With the advent of remote sensing, it has been possible to prepare this dynamic resource map at various levels of confidence. However, the application of multi-spectral classification techniques in extracting vegetation classes has been inconsistent because of similarities in spectral responses (8,4). The problem is more serious with the digital techniques applied to heterogeneous hilly terrain. The other problem in the collection of land-use data is the presence of clouds and their shadows during the monsoon period. In addition, it is also important to map the agricultural land-use pattern of both monsoon (*kharif*- when most of the crops are matured and harvested) and post-monsoon (*rabi*- cloud-free images showing vegetation in the upland areas)) seasons together in the rural watersheds. Therefore, multi-seasonal remotely sensed images of Landsat-TM digital (kharif) and IRS-LISS II FCC (rabi) were used. In addition, multi-thematic maps of soil, slope and drainage were used to generate multi-disciplinary knowledge-based rules to overcome the above inherent problems in the hilly terrain. These maps were input and stored as separate layers in the GIS for integrated analysis. The above GIS data layers and the informed opinions, in the form of knowledge-based rules drawn from multi-disciplinary experts and the knowledge of local land-use patterns plus the field checking, were incorporated in the map to consolidate the agricultural land-use pattern of this heterogeneous highland. To give a few examples:

- If Landsat-TM (Kharif class) = Thick Forest and IRS and LISS-II (Rabi) = Thick Forest; Then class = Thick Forest.
- If Kharif class = Sparse Forest and Rabi class = Open (with/without scrub) Area or Degraded Pasture; Then class = Open (with /without scrub) Area or Degraded Pasture, respectively.
- If Kharif = Sparse Forest and Rabi = Cropped; Then class = Cropped.
- If Kharif = Cloud Cover and Rabi = Thick Forest; Then class = Thick Forest.
- If Kharif + Rabi = Vegetation, Drainage density = Low, Soil = Typic Chromusterts and slope = <5 degrees; Then the class = Cropped.

These informed-opinions, codified in the form of *'if-then'* type of rules, were used to improve the classification accuracy. Initially, the correspondence between the visual and digital classification maps was at best 45%. After applying the rules on the classification output, the accuracy increased to 85-100%. (2). In the process, the visual and digital classification techniques interacted to improve the classification system. Finally, the GIS-assisted improved land-use map consists of five major categories, which were selected from the conservation planning point of view: agriculture, thick forest, sparse forest, degraded pastures and open (with/without scrub) lands. The introduction of multi-disciplinary expert rules provides an extension to the traditional methods of satellite-derived classification that should enable more relevant, and accurate, land-use/cover map preparation.

A collective approach comprising satellite data (IRS) and topographic maps was used for physiographic units. The soil associations of each physiographic unit were established by studying soil profiles in sample strips and by random checking outside the sample strip areas, classifying the soils according to an established soil taxonomy (12). Finally, a soil map at 1:50 000 scale was prepared by combining the soil information in each delineated physiographic unit. The developed and moderately deep (50-90 cm) black cultivated soils (Typic Chromusterts) generally occupy the valleys and plains of the watershed. Undulating uplands and subdued hills have degraded pastures or open scrub and partly cultivated lands. These units can be classified into the association of Lithic Ustorthents/Vertic Ustropepts with shallow soil depth (20-50 cm). Underdeveloped and very shallow (<20 cm) soils (Lithic Ustorthents) cover the hilly regions with steep slopes; these are mainly forest areas.

The contours and high points were digitized from 1:50 000 SOI topomaps (20 m interval) to generate the *Digital Elevation Model (DEM)* and the slope map with the help of the GRAM package. The watershed was divided into three major slope classes for the evaluation of soil erosion and priority sub-watersheds delineation survey: 1) gently sloping lands (0-8 degrees); 2) moderately sloping lands (8-18 degrees); and 3) steeply sloping lands (>18 degrees). Steeper slopes promote concentrated run-off and exposed rocks in some places. Moderate slopes support mostly degraded pastures or open scrub lands and have moderate to high run-off potential. Gently sloping lands covered with moderately deep cultivated black soils have low run-off potential. Once the contours are digitized, GRAM allows one to categorize any number of slope steepness classes as needed.

An isohyetal map was compiled manually from ten years of mean annual rainfall data from six meteorological stations available in and around the watershed area. The watershed was divided into two rainfall zones: a < 1500 mm low rainfall zone, and a > 1500 mm high rainfall zone.

The drainage network was generated from SOI toposheet (of 1975) and the high order river course systems were mapped from Landsat-TM imagery (of 1989). The drainage density (total length of streams/unit area) was calculated for each sub-watershed and divided the watershed into low, medium and high drainage density zones. 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 divided into 33 sub-watersheds, which are smaller hydrologic 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 as a viable working size for conservation planning.

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

5. Database Analysis

5.1 Soil erodability assessment

Soil erosion is the resultant of interplay between watershed environmental factors such as soil, topography, drainage, rainfall and land-use pattern, which are available from different sources/systems. In order to study soil erosion, it is important to integrate these data. GIS is the most effective and viable tool for considering the interaction between the spatially distributed resources. We made a number of useful combinations of the data via overlay analysis and created '*integrated resources units (IRUs)'*. Each IRU comprises the watershed resources of soil, land- use, slope, rainfall distribution and drainage buffers. The link between IRU and the soil erosion intensity unit is provided by rules. In the construction of the decision-rules, the multi-disciplinary expertise, the knowledge of the local terrain parameters and field observations were taken into consideration, in addition to the author's expertise in soils, land-use planning, remote sensing and GIS. Two examples are:

- If 5^0 slope, other drainage area, Typic Chromusterts, <1500 mm rainfall with thick forest; Then class = slight to moderate erosion risk.
- If > 18^0 slope, 1-2 drainage orders, Typic Ustorthents, > 1500 mm rainfall zone with open areas; Then class = very severe erosion risk.

Application of these multi-disciplinary expert rules permits mapping of the erosion intensity that is likely to occur at any given location, without any subjective bias (6). The soil erosion map was generated with four categories showing slight to moderate (< 20 t/ha/yr), moderate to severe (20-30 t/ha/yr), severe (30-50 t/ha/yr) and very severe (> 50 t/ha/yr) soil erosion intensity units.

5.2 Conservation planning

A major step in the conservation-oriented planning process is making an inventory and classification of the watershed and then judging its capacity to support land-use on a sustained basis and also to avoid uses that degrade the land. Erosion relates factors such as slope steepness and soil depth can be yardsticks against which to judge the suitability of alternative land-uses and the conservation requirement (9). The first step in this process is to create a basic unit by overlay analysis. Each unit comprises physical resources of soil depth and slope steepness classes, (unlike in IRUs where all the biophysical units are considered) and, hence, were called *`integrated physical land units` (IPLUs).* The link between IPLU and the treatment-oriented land use planning scheme is provided by information-based rules. In the implementation of these rules, the land-use capability classification formulated by Sheng and Stennett (10) was mainly used, modified according to knowledge of local terrain parameters and field observations, plus the expertise of the author in the subject. These rules and factors were used to generate a sustained land-use system in the watershed with proper soil and water conservation measures. Employing this system for land-use planning would be a safeguard against soil erosion and other environmental threats.

Conservation planning in watersheds is expensive and we, therefore, require a selective approach for identifying smaller hydrological units (or sub-watersheds of individual tributaries or the lowest order, or a group of such tributaries) to advice resource management programs more efficiently. Hence, a priority sub-watershed delineation survey was carried out in the watershed (5) using the All India Soil and Land Use Survey's *Sediment Yield Index (SYI)* model (7). The methodology to prioritize the watersheds includes:

- generation of information databases of soil, slope, drainage and density, land-use pattern and delineation of sub-watersheds
- generation of IRUs by overlay analysis
- assignment of weights and delivery ratio values to IRUs based on the compounded effects of the environmental factors in terms of the erodability and erosivity potential of IRUs.

On the basis of SYI values, the watershed was divided into four priority classes: low (1000-1099), medium (1100-1199), high (1200-1299) and very high (> 1300) priority sub-watersheds. The significant variation in *SYI* values between sub-watersheds calls for a conservation-planning scheme like the one developed with GIS in the present study. The high and very high priority sub-watersheds could be treated with the land-use planning system suggested here to try to conserve the ecosystem in the watershed. If the appropriate conservation measures are given priority, there would be less erosion, and subsequently investments to control soil erosion, or worse, to rehabilitate the affected lands, can be reduced (3).

6. Conclusions

The case study presented here suggests that the evaluation of agro-ecological characteristics from primary data, soil erosion assessment and aspects of conservation management, could lead to the generation of a WATMIS for a watershed (Figure 1). The development of a WATMIS in the context of local needs and problems, population and infrastructure leads to computation of resource surpluses and shortfalls at the present level of food/fuel demand and supply. Future demands for sustainable development of the watershed can then be formulated based on which thrust areas in each sector (or sub-watershed?), can be identified.

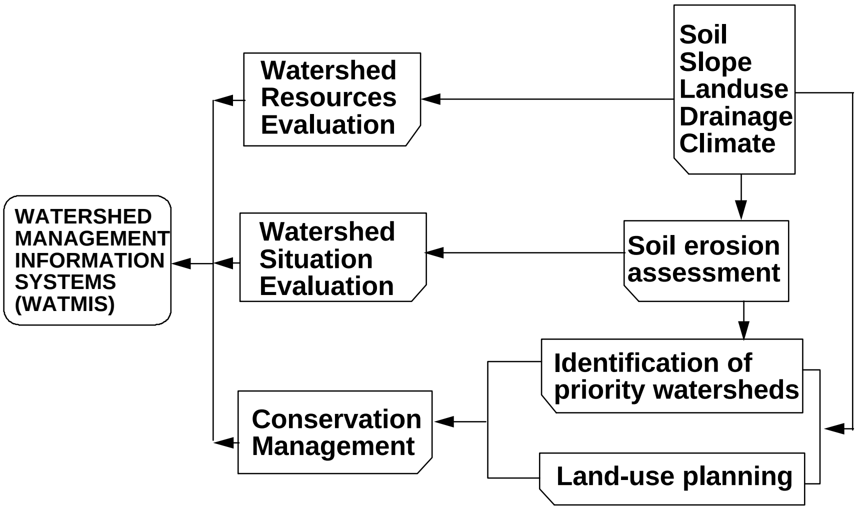

Figure 1. Watershed management information systems.

The raster based GIS provides an easy method of integrating the watershed resource data into useful maps. Vector data are transformed to a grid cell by interpolation or polygon conversion. Once in raster form, per pixel logical combinations are simple and could almost be handled in a standard database.

IRUs and IPLUs, generated for different purposes in the study, act as the strategic unit for various watershed management aspects as they exhibit strong uniformity in bio-physical attributes and are expected to respond similarly to given intensities of human use and management strategies.

The knowledge-based rules used in watershed management planning were expressed as the probability of an item occurring given a particular hypothesis. The rules are the most subjective aspect of the system: they are heuristic, estimated from the knowledge of the pedologist and other resources experts and form a continuum between true and false depending on how sure we are that the rule is true or false (11). The knowledge bases, with further research and testing in different and larger areas, could lead to future decision-support systems for watershed management programs.

Sophisticated methodologies, such as image processing and GIS, are useful tools for planning resource use and management at regional scales. These tools could be further improved by finer resolution terrain analysis, incorporating many more ecological and socio-economic variables, incorporating informed opinions from experts and local people (the experiential knowledge-bases), and employing effective extrapolation of expert system / neural network analysis. Eventually, with this improved approach, the local governmental bodies should be able to possess a highly versatile and responsive system that enables their resource managers to assess the breadth and depth of their needs in a geographically precise and consistent manner. It is hoped that the study reported in this paper can illustrate the advantages of *off-the-shelf* software and GIS technology in providing rapidly the alternative management strategies for large-scale resource planning.

The study also ensures the ability to monitor the dynamic changes of the watershed, particularly the land-use pattern, by remote sensing at periodic intervals, and to redefine 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 other areas of the hilly watershed ecosystem in the Western Ghat mountainous zone. Although it is an early airing of results obtained from the methodology described, the introduction of multi-disciplinary expert's informed opinion may provide an extension to the traditional methods of watershed management programs that should enable us to generate and/or evaluate different conservation scenarios.

7. Acknowledgements

This research project was financed by a research grant from the Department of Science and Technology, Government of India (through SERC Program - ES/23/077/89). The author wishes 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.

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