GIS-based technologies for watershed management

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Due to the ever-increasing demand on water resources, the pressure on its judicious utilization is also increasing. Besides being precious, this resource is also complex to manage on account of its dynamic behaviour. It implies that the response to a unit of precipitation input is dependent on the state of wetness of the land mass and the environment prevalent at that time. Therefore, the changing weather conditions as well as the spatial variability of land mass result in nonlinear behaviour of the response of the watersheds.

In a place like India, where emphasis is being placed on making the local-level users participate in the management of natural resources at the watershed level, it is imperative that these local-level organizations be strengthened by providing the integrated watershed management tools which are user-friendly, but still use all the scientific knowledge to arrive at the appropriate decisions.

This article demonstrates the use of GIS-based modelling framework for local-level planning, incorporating the sustainability aspects of watershed development. A case study has been taken in Bijapur district, Karnataka to demonstrate the implementation of these new technologies for watershed prioritization.

WATER is a precious natural resource and at the same time complex to manage. There is no doubt that India has done well in the sector of water resources development in the form of major, medium and minor irrigation projects, in the last fifty years, which has in turn played an important role in the progress of the country. Water resources development is a continuous process which has to be resorted on account of ever-increasing demands. The major irrigation projects cater to millions of hectares of land, whereas at the other extreme, local-level projects such as small ponds/tanks involving small structures may also be used to fulfil the requirements of a small community at the village level. It has been noticed that once these projects have been created, their proper operation and maintenance is invariably ignored. There have been many instances where implemented projects have been found to be responsible for creating environmental problems in the society. Those concerned with the water sector have shared the above concerns. Policies are being made and a number of new programmes are floated to address the water-resources problem. A common framework that can be used for effective planning, development and management of these programmes in an integrated manner is invariably missing. The integrated watershed management (IWM) approach has been globally accepted as the best for natural resource management, but is rarely or partially implemented because of the lack of required framework and/or technical know-how.

This article puts forward a scientific approach to handle the IWM strategy through a case study implemented to demonstrate the watershed prioritization exercise. All the other requirements of IWM can also be fulfilled using the same framework.

Integrated watershed management philosophy

IWM planning is a comprehensive multi-resource management planning process, involving all stakeholders within the watershed, who together as a group, cooperatively work towards identifying the resource issues and concerns of the watershed, as well as develop and implement a watershed plan with solutions that are environmentally, socially and economically sustainable.

In India, the IWM efforts go back to 1970. There have been many changes in the implementation strategies during the following years. Until 1995, watershed development projects were officially coordinated by multi-sectoral programmes (with differing objectives) launched by the Government of India. After review in 1999 by the Ministry of Rural Development and the Ministry of Agriculture, a common set of operational guidelines, objectives, strategies and expenditure norms were established for watershed development programmes in 2001. These are implemented through programmes such as DPAP (Drought-Prone Area Programme), DDP (Desert Development Programme) and IWDP (Integrated Watershed Development Programme). The guidelines encourage the active involvement of non-governmental organizations, semi-governmental institutions and private enterprises, universities and training institutions. However, concerns are being raised that emphasis in watershed development programmes is still firmly based on the belief that water

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is an infinite resource, through development of groundwater abstraction and water harvesting techniques[1].

IWM does not merely imply the amalgamation of different activities to be undertaken within a hydrological unit. It also requires the collation of relevant information so as to evaluate the cause and effect of all the proposed actions. The watershed is the smallest unit where the evaluation of human-induced impacts upon natural resources becomes possible. Therefore, although the 'Panchayat' remains the preferred implementation unit, the watershed should be the evaluation unit used in assessing impacts.

As the impacts resulting from actions taken at the Panchayat/watershed level will be experienced at a higher level within the drainage basin, the assessment of these impacts will require the availability of a framework which enables the mapping of such units and their entities, and the interconnections at the Panchayat level and at the higher catchment level. Such a framework will need regular maintenance and updating to reflect fully the most accurate ground-truth data or the infrastructure requirements for planning and management of natural resources collected by the relevant departments. This framework, once available, could be used by all the line departments and updated by the relevant departments, which have designated areas of jurisdiction over the data entry. The format should be made consistent with local to State and national level structures as well as the corresponding watershed, sub-basin and basin-level structures.

All the information which is required for integrated planning and management is not readily available at the desired scale of a watershed. This is true with respect to the quantity of water, both surface and ground. Although the information on local water availability as well as its variability in time is essential for proper planning and management, measurement of these quantities in terms of flows is not financially viable at such scales. Hydrological simulation modelling is an effective tool to take care of this essential requirement of IWM. In the present study one such model has been deployed to simulate the quantity of water and sediment erosion in the sub watersheds of the study area. A short description of the model has been presented in the following section.

SWAT hydrological model

The SWAT (soil and water assessment tool) model, developed by the USDA Agricultural Research Service[2], simulates the land phase of the hydrologic cycle in daily time steps. Routines are also included for simulating the detachment of sediments from the watersheds and their transport through the drainage systems. The SWAT model is designed to route water and sediments from individual watersheds, through the river systems. It can incorporate the tanks and the reservoirs/check dams off-stream as well as on-stream. The agricultural areas can also be integrated with respect to its management practices. The major advantage of the model is that unlike the other conventional conceptual simulation models, it does not require much calibration and therefore can be used on ungauged watersheds.

The model can be used for the assessment of existing and anticipated water uses and water shortages. The model provides a complete accounting of the quantity of water that is supplied to the land by precipitation; enters the streams as surface run-off; is used and returned to the atmosphere by natural vegetation, agricultural crops and evaporation, and that percolates through the root zone and a part returns as groundwater contribution.

For modelling purposes, a watershed is partitioned into a number of subwatersheds. The use of subwatersheds in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils different enough in properties to impact hydrology. Input information for each subwatershed is grouped with respect to unique areas of land cover and soil, which are known as hydrologic response units or HRUs. These HRUs behave in a hydrologically similar manner to the inputs of precipitation.

Model outputs include all water-balance components (surface run-off, evapotranspiration, lateral flow, recharge, percolation, sediment yield, etc.) at the level of each subwatershed and at daily, monthly or annual intervals. These technologies have been integrated and promoted through an UNDP (United Nations Development Programme) sponsored project titled 'GIS based technologies for local level development planning', handled by the Department of Science and Technology, New Delhi. The components of the technologies presented here through the case study were formulated by the authors during the course of the UNDP project.

Case study

A demonstration case has been developed on the Doddahalla watershed, wherein micro-watershed prioritization has been carried out using criteria cutting across hydrological, demographic and socio-economic parameters[3]. Collation of scientific information generated through modelling with other required information such as demographic, socio-economic, etc. is required for taking local-level decisions.

Description of the study area

The Doddahalla watershed in Bijapur district, northern Karnataka, with an area of about 61,000 ha has been modelled using SWAT. This is a chronically drought-prone district with a large agrarian population predominantly depending on rainfed agriculture.

Upstream watershed (head water area of the main drainage system) with an area of 31,000 ha is being treated and the remaining 30,000 ha area belonging to the downstream watershed (the lower area on the main stream) has been used for detailed analysis in the present study. This part of the watershed covers 30 villages of Indi and Bijapur taluks.

Modelling Doddahalla watershed with SWAT

GIS (Geographical Information Systems) is used as a preprocessor to the SWAT model. Digital elevation model (DEM) was generated using the digitized contours. DEM along with the digitized drainage was used to automatically delineate (using GIS-based terrain analysis algorithm) the subwatersheds. The subwatershed layer was overlaid with the landuse and soil layer to derive the HRUs. Model inputs, including soil, weather, groundwater and management required for each HRU were automatically derived using the GIS interface. The entire area, including the upstream watershed was divided into 50 subwatersheds and 175 HRUs. The upstream watersheds have also been modelled for assessment of water and sediment generation to be used in conjunction with the downstream watersheds of the study area. The daily weather data (1969–1990) for Bijapur station were used for rainfall and temperature.

The outputs of the model, namely the water availability (mm/yr) and sediment yield (t/ha) have been depicted in Figure 1 for each subwatershed of the study area. These are two of the many elements required for the watershed prioritization, but seldom available.

The watershed management involves a large number of guiding principles such as conservation of natural resources, integrated development of natural as well as social resources, *in situ* moisture conservation, sustainable farming system, adoption of ridge-to-valley approach, livelihood support for landless families, democratic decentralization in decision making, equity for resource-poor families and empowerment of women, etc. Though the priority given to these elements varies from State to State, NWDPRA (National Watershed Development Project for Rainfed Areas) guidelines have been invariably accepted. These guidelines recommend combining physical and socio-economic criteria. Under the physical criteria, the priority-wise entities that should be followed include: head-water watersheds with erodability, land degradation, water scarcity problem, rainfall less than 750 mm, net cultivated area not more than 20%, irrigated area not exceeding the State average or 30%, and with no long-duration crop or water-intensive crops. Since the financial allocation is done with respect to the administrative boundaries (village in the present case), one of the criteria is to take watersheds that cover majority area of the villages.

With respect to socio-economic criteria, priority is given to villages/watersheds having large economically weaker population, SC/ST population, uniform land holdings and many others depending on local priorities.

Each element of the prioritization criteria (physical and socio-economic) was created as GIS layers taking a subwatershed (with alphanumeric nomenclature for ease of depiction) or village as the mapping unit. Figure 2 depicts these subwatersheds along with the village boundaries. The overlay analysis has been performed to satisfy the laid-down criteria in the sequence of priority. The first

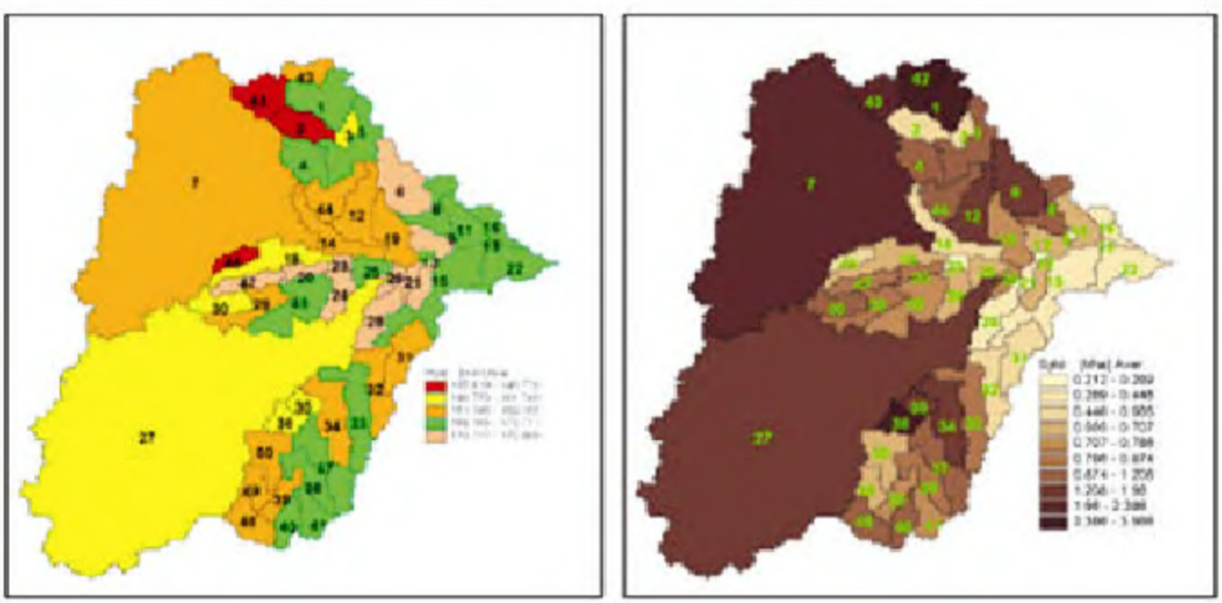

Figure 1. Water availability and sediment yield map (20-year average).

level of physical criteria of extent of average annual rainfall, head-water watersheds and watersheds with maximum soil erosion and minimum water availability, were implemented on the study area. This analysis resulted in identifying a cluster of seven subwatersheds for further analysis. It may be mentioned here that without the availability of the two crucial elements of water availability and sediment yield at the subwatershed level, which has been made possible through hydrological modelling, such delineation would not have been possible.

In order to implement the next criterion of taking up watersheds which are covered by maximum part of the village(s), the overlay of the selected seven subwatersheds with the village boundaries was performed. Four (4D5A6C2B, 4D5A6C2C, 4D5A6C2D and 4D5A6C2E, inside the circle in Figure 2) of the seven subwatersheds were found to cover majority area of the two villages, Ainapur (63%) and Burnapur (50%). The other analysis pertaining to the socio-economic aspects such as number of people below the poverty line, SC/ST population, size of the land holding, etc. was also performed in a similar manner. The four subwatersheds, namely 4D5A6C2B, 4D5A6C2C, 4D5A6C2D and 4D5A6C2E qualified all these criteria as well. Thus this contiguous set of subwatersheds was recommended to be taken as the priority area for further analysis and treatment.

Strategies for watershed development

Having identified the priority watersheds, the next action was to generate detailed information commensurate with the implementation of new technologies and subsequent control and operation of generated resources. A detailed survey was conducted over these subwatersheds to generate the detailed terrain information. Figure 3 shows the overlay of contours generated from the survey on the digitized village revenue plot from the cadastral map.

The detailed survey was essential to generate a reasonably accurate DEM for making use of the latest technologies of GIS to help in handling the water resources development at the local level. This DEM has been used to generate the local drainage (Figure 4), which in turn is used to identify the possible locations of the water-harvesting structures.

Selection of a suitable site is important in planning and construction of harvesting structure. Demonstration has been made through interface on ArcView with Spatial Analyst extension for site selection of water-resources structure (ArcView extension by www.esri.com). Profiles drawn on the DEM would give the hydraulic characteristics of the terrain such as spread area and volume of storage, with respect to the crest level of the barrier created across the drainage. This, when superimposed on the

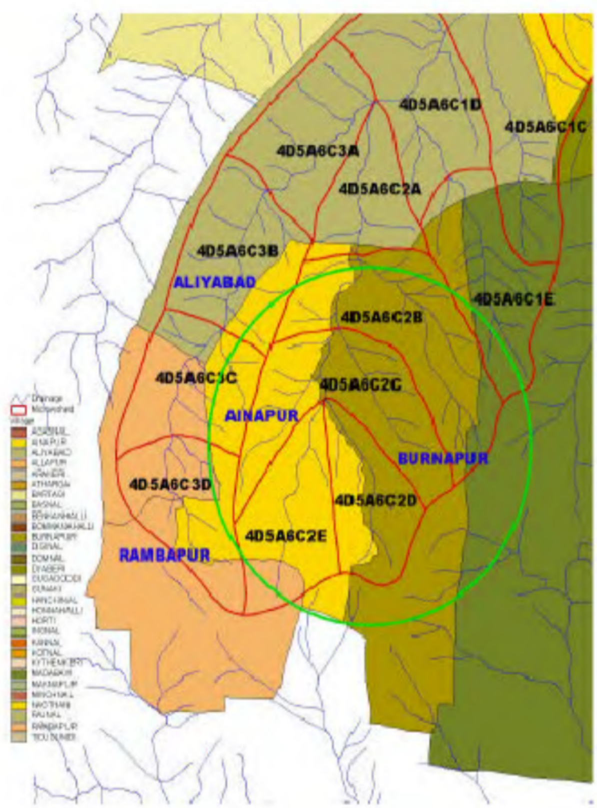

Figure 2. Watershed and village interaction.

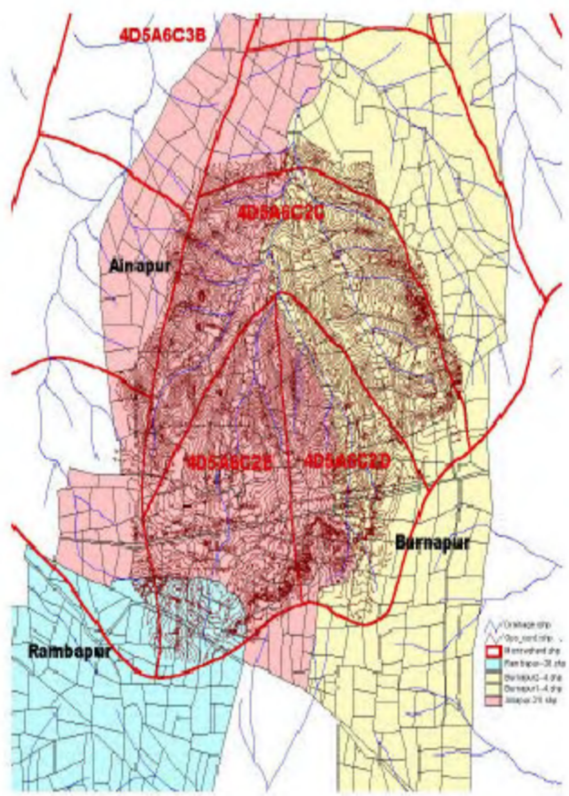

Figure 3. Details of survey area and 1 m interval contour with microwatershed boundary.

plot/village maps, provides the inundated area. This kind of application can rapidly provide the first-level feasible sites which can then be field-tested for implementation. Figure 5 shows one such depiction with two alternate sites with different design parameters and resultant computations made by the application. Site1 produces a volume of 0.8 ha m and a spread area of 3.02 ha with respect to crest height of 2.0 m, whereas Site2 produces a volume of 9.0 ha m and a spread area of 6.93 ha with respect to crest height of 4.0 m.

The above example is a demonstration of latest tools to derive the appropriate information through analysis and modelling to help in the local-level planning for IWM. This also has the strength of making these decisions highly understandable to all the stakeholders and thereby enhance the local-level participation.

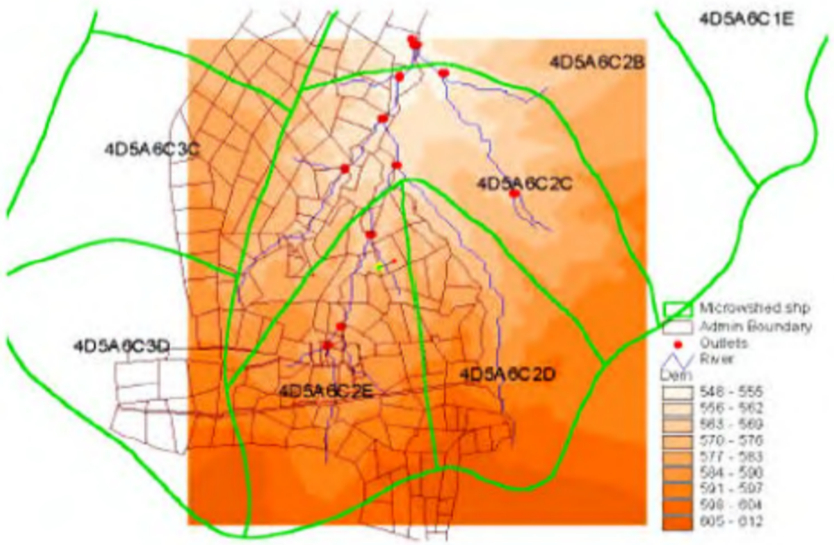

Figure 4. Digital elevation model with local drainage overlaid with micro watershed and plot boundaries.

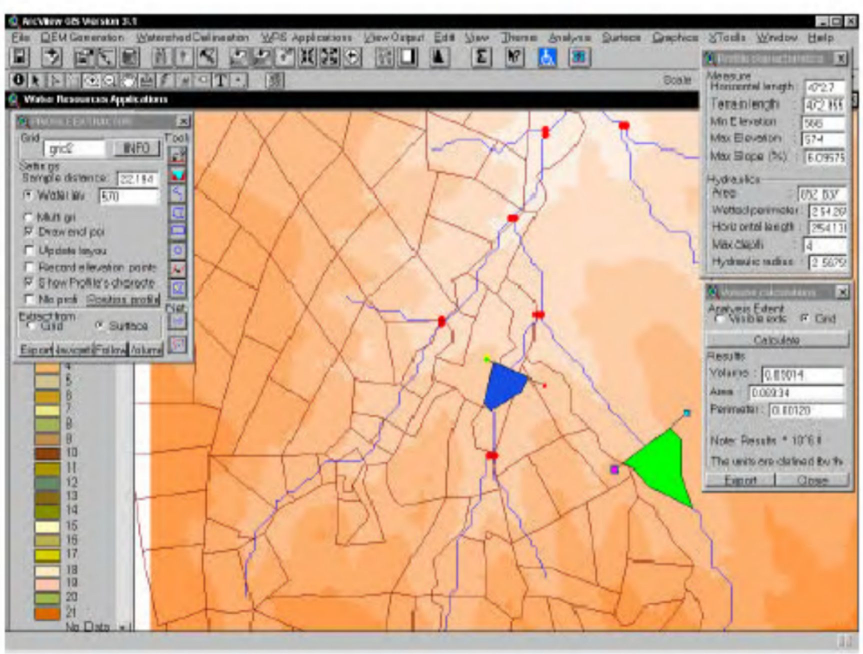

Figure 5. Locating water-harvesting structure.

Conclusion

Watershed prioritization is an important aspect of planning for implementation of the watershed management programme. First of all, demonstration has been made about implementation of the hydrological model at the watershed scale to generate the estimates of water and sediment yield at the micro-watershed level to be used in the planning process. Such information is crucial and invariably not available at such scales. Some peripheral interfaces have been designed to help the planners of the watershed programme. Two such applications, one for finding the interaction between the administrative and watershed boundaries that shall help in allocation of financial resources with respect to the watershed boundaries and the other to locate the water-harvesting structures, which is a common feature in the watershed management programme, have been formulated and demonstrated. Besides helping in siting of the structures, the spatial tool also helps in estimating the related parameters like the water spread area and available water storage capacity at that location. These applications not only suffice the general requirements of the end-users, but also go much further in ensuring that a scientific character is brought about in this crucial sector of watershed management.

This application is also useful to help the watershed managers in objectively prioritizing the watersheds with respect to the stipulated norms. The application can also be used for monitoring and evaluation of the watershed programmes which is an important component, but is invariably missing.

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