IDENTIFICATION OF POTENTIAL RUNOFF HARVESTING SITES IN A WATER SCARCE RURAL WATERSHED USING GIS APPROACH

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ABSTRACT

Water scarce regions in western parts of India are subject to various hydrological constraints. The resource poor agricultural communities that depend on rainfed agriculture are the hardest hit. Rainfall patterns in these arid and semi-arid areas are unpredictable. Frequent occurrence of mid-season dry spells or late monsoon result in poor soil water availability during growing season, reduced crop yield and increased risk of crop failure in severe cases. Therefore, in such circumstances, the ability to efficiently harvest the rainfall runoff is of critical importance to maintain agricultural production in an economically and environmentally sustainable manner. However, implementation of runoff harvesting in an extensive way, without any adverse impacts on downstream hydrological systems, requires a better understanding of the hydrological processes.

The representation of spatial variation in land characteristics such as slope, soil, and land use as well as rainfall is important in identifying potential runoff harvesting sites. Thereafter, modeling of the hydrological response in watersheds where runoff harvesting is being considered can be performed and likely impacts can be assessed. At present, there is a growing need for cost effective and time saving methods for identifying areas that are suitable for implementing runoff harvesting technologies particularly in rainfed rural agro-ecosystems as a means to supplement water availability. Advances in computer technology and Geographic Information System (GIS) provide useful tools that allow efficient integration of spatial characteristics of watersheds leading to improved representation of hydrological processes in the landscape.

In this study, a small rural semi-arid watershed, located in the Jaisamand lake Catchment in Aravalli Hills in Udaipur district of Rajasthan, is considered. The watershed is predominantly inhabited by tribal communities. Scarcity of water together with lack of proper natural resource management have resulted in degradation of land and water resources, and, poor social and economic conditions in the region. To cope with water scarcity, there is a need to implement rainfall runoff harvesting to develop the water resources in a sustainable manner and mitigate the adverse impacts of droughts, stabilize agricultural production as well as reduce the community's vulnerability to water shortage.

The study identifies priority areas for runoff harvesting in the rural watershed with the use of GIS. For small watersheds, the Natural Resources Conservation Service (NRCS) method is the most widely used technique for estimating surface runoff for a given rainfall event. It considers the relationship between landcover and hydrologic soil group, which together make up the curve number. A curve number is used to ascertain how much rainfall infiltrates into soil and how much rainfall becomes surface runoff. Traditionally, an area weighted average curve number for the entire watershed is used to study the runoff of a watershed. The detail of spatial variation is often lost. This study takes help from GIS to produce curve number and runoff maps with the help of ArcCN-Runoff tool available in ArcGIS. Slope, derived from the Digital Elevation Model (DEM) of the watershed, along with the NRCS curve number were used to determine the runoff potential. Locating optimal sites for runoff harvesting was based on the physically derived potential runoff map as well as the socio-economic factors such as distance to croplands and rural settlements. Thus, through GIS analysis, potential runoff harvesting sites are identified in relation to the areas that concentrate runoff and where the stored water will be appropriately distributed.

Output of this study, based on integrated GIS modeling system, is presented using 'suitability maps' developed for potential runoff harvesting sites for the rural watershed. It is concluded that providing an accurate spatial representation of the runoff generation potential within a watershed is an important factor in developing a strategic runoff harvesting plan for any watershed. The use of GIS approach to facilitate this process improves the accuracy level for locating suitable areas for runoff harvesting in view of the GIS capability to utilize spatial information in an integrative manner and spatially displaying it through maps.

INTRODUCTION

Water scarce regions in western states of India in Rajasthan and Gujarat are subject to various hydrological constraints. Agriculture and several of the other economic activities in drought prone areas of arid and semi-arid regions depend on rain. Rainfall patterns in such arid and semi-arid areas are unpredictable. An annual rainfall of less than 300 mm characterizes most of the drought prone areas but several regions in semi-arid areas receiving upto 1000 mm annual rainfall also experience frequent droughts. In most regions of water scarcity (except extremely arid lands), the shortage of water is not caused by low rainfall as is normally perceived but rather by a lack of capacity for sustainable management and use of available rainwater. Thus, one of the major challenges is how to deal with the poor distribution of rainwater leading to short periods of too much water and flooding and long periods of too little water.

The hardest hit, due to the unpredictable rainfall pattern, are the resource poor agricultural communities that depend on rainfed agriculture. Frequent occurrence of mid-season dry spells result in poor soil water availability during growing season, reduced crop yield and increased risk of crop failure in severe cases. In such circumstances, the ability to efficiently harvest the rainfall runoff is of critical importance to maintain agricultural production in an economically and environmentally sustainable manner. The water resources generated locally would provide water for supplementary/deficit irrigation, help in meeting domestic and livestock needs, enhance groundwater recharge and reduce storm water discharges. Moreover, efforts made to store rainwater-runoff could reduce the constraint of opting for only rainfed cultivation due to the lack of irrigation facilities. However, implementation of runoff harvesting in an extensive way, without any adverse impacts on downstream hydrological systems, requires a better understanding of the hydrological processes.

Water Harvesting and Conservation Techniques

Water harvesting is the process of collecting rainfall as runoff from a larger catchment for use in a smaller target area. Different traditional and innovative techniques can be adopted for runoff farming water harvesting, surface storage water harvesting and groundwater recharge. Some of the successful water resource development strategies are: in-situ rain water harvesting (includes measures such as field bunding, contour bunding, ridging, conservation furrows, and contour cultivation), checkdams, tanks etc.

The representation of spatial variation in land characteristics such as slope, soil, and land use as well as rainfall is important in identifying potential runoff harvesting sites. Thereafter, modeling of the hydrological response in watersheds where runoff harvesting is being considered can be performed and likely impacts can be assessed. At present, there is a growing need for cost effective and time saving methods for identifying areas that are suitable for implementing runoff harvesting technologies particularly in rainfed rural agro-ecosystems as a means to supplement water availability.

Geographic Information System (GIS) provides a useful approach because it provides a framework for collecting, storing, analysing, transforming and displaying spatial and non-spatial data for particular purposes (1, 2).Advances in computer technology and GIS provide useful tools that allow efficient integration of spatial characteristics of watersheds leading to improved representation of hydrological processes in the landscape (3). Conventional methods of runoff measurement are time consuming, costly and difficult because of inaccessible terrain in many of the watersheds. Use of new tools, for instance GIS, to generate supporting land-based data for conserving soil and water resources in watershed planning is very much needed. The Natural Resources Conservation Service (NRCS) method is the most widely used technique for estimating surface runoff for a given rainfall event. The method utilizes a curve number (CN) to ascertain how much rainfall infiltrates into soil and how much rainfall becomes surface runoff. Many researchers (4-7) across the world have utilized the Geographic Information System (GIS) technique to estimate runoff curve number value. In India, Pandey and Sahu (4) pointed out that the land use/land cover is an important parameter input of the NRCS-CN model. Nayak and Jaiswal (5) found that there was a good correlation between the measured and estimated runoff depth using GIS and CN. They concluded that GIS is an efficient tool for the preparation of most of the input data required by the NRCS curve number model.

In this study, NRCS-CN method is used in prioritizing the potential runoff harvesting sites in a water scarce rural watershed located in Jaisamand Lake Catchment in Rajasthan using GIS techniques. The adopted methodology is a variant of the technique previously reported (3). ArcGIS 9.3 and ArcCN-Runoff tool (6) is employed to produce curve number and runoff maps.The study emphasizes use of GIS techniques in identification of runoff harvesting sites using landcover, slope and socio-economic factors such as distance to croplands and rural settlements.

STUDY AREA

The Jaisamand Lake Catchment is located in Aravalli Hills in the Udaipur district of Rajasthan. Located in a semi-arid region, the Jaisamand lake is Asia’s second largest artificial water storage reservoir about 52 km south east of Udaipur city, bounded by Longitude $73^0$45' E to $74^0$25'E and Latitude $24^0$10' N to $24^0$35' N. The Jaisamand Lake Catchment is an area of low hills formed of eroded hard-rock comprising part of the Aravalli Hills Range. Rainfall with a mean value of 650.3 mm occurs during months of June-September typically as several intense storms and light showers spread over a period of about 20-30 days. Rivers flow only for a few months following the rains with droughts forming a normal feature of the basin. The ephemeral nature of the surface water forces reliance on shallow groundwater which is variably recharged during the monsoon season. The area is predominantly inhabited by tribal communities and some 30% of the population currently lives below the poverty line surviving on meagre resources. The principal activities that support the livelihood system are agriculture, animal husbandry and wage employment. The villagers in the area depend on rainfed agriculture, which is for four months, and mostly remain on wage employment at nearby towns during remaining period. Lack of sustainable food and fodder security system and non-availability of non-farm based economic activity gets aggravated during droughts. Scarcity of water together with lack of proper natural resource management have resulted in degradation of land and water resources, and, poor social and economic conditions in the region. To cope with water scarcity, there is a need to implement rainfall runoff harvesting to develop the water resources in a sustainable manner and mitigate the adverse impacts of droughts and stabilize agricultural production.

Savna Macro Watershed

Savna macro watershed is located in the Jaisamand lake catchment (refer Fig. 1) between longitude 74°05′28″ E to 74°08′44″ E and latitude 24°21′30″ N to 24°26′36.4″ N. Drainage pattern of the watershed is generally dendritic type. The elevation ranges from a minimum of 309 m to a maximum of 443 m above msl. The geology of the region is hard rock comprising granite, gneiss, phyllite and schists. Most part of the area has potable groundwater and is good for irrigation purpose. Surface water resources are scarce. The main source of irrigation in the area are wells (irrigated area 86.4%) followed by ponds/tanks (irrigated area 13.2%). The area comprises of forests, unculturable land, pastures, culturable waste, fallow land and cropped area. Maize, wheat, gram and mustard are the major crops grown in the area. Maize is grown on sloping land as well, resulting in varying degrees of productivity, while wheat and mustard are grown on level fields.

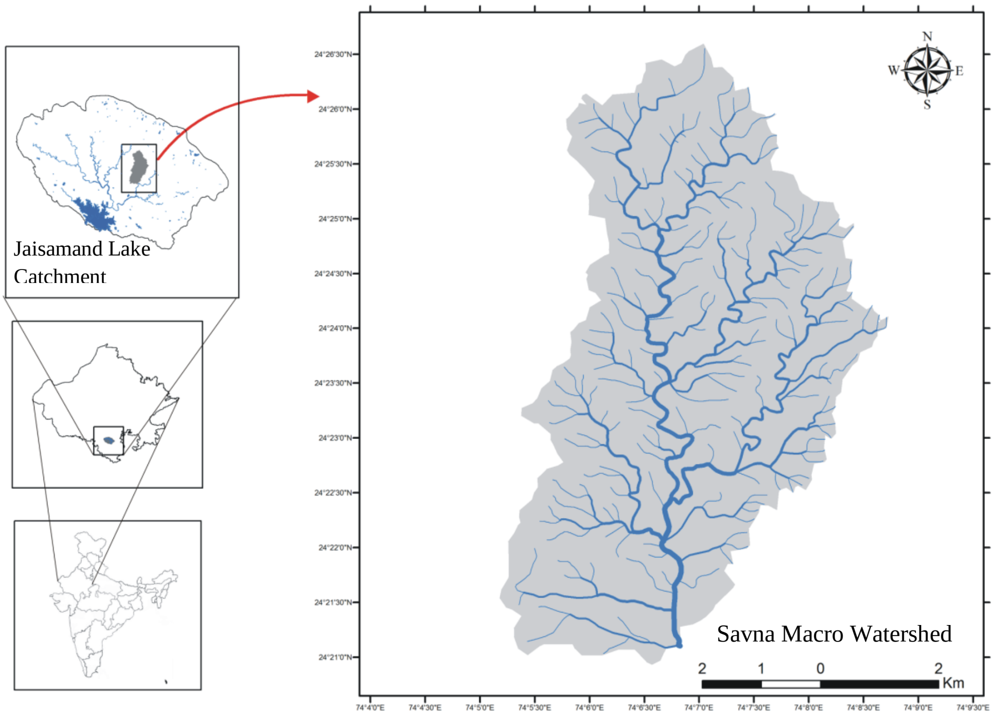

Fig. 1 Study area

DATA PROCESSING

The identification of suitable runoff harvesting sites requires information based on physically derived watershed characteristics for understanding the watershed's hydrological response. Several criteria have been suggested for selecting runoff harvesting sites such as soil suitability, slope suitability, land use, and harvesting potential for the upstream catchment and socio-economic parameters such as distance from croplands and settlements (3, 8). Figure 2 shows the major steps taken to process the collected datasets and generate useful output in the form of runoff potential and suitable runoff harvesting areas using GIS tools.

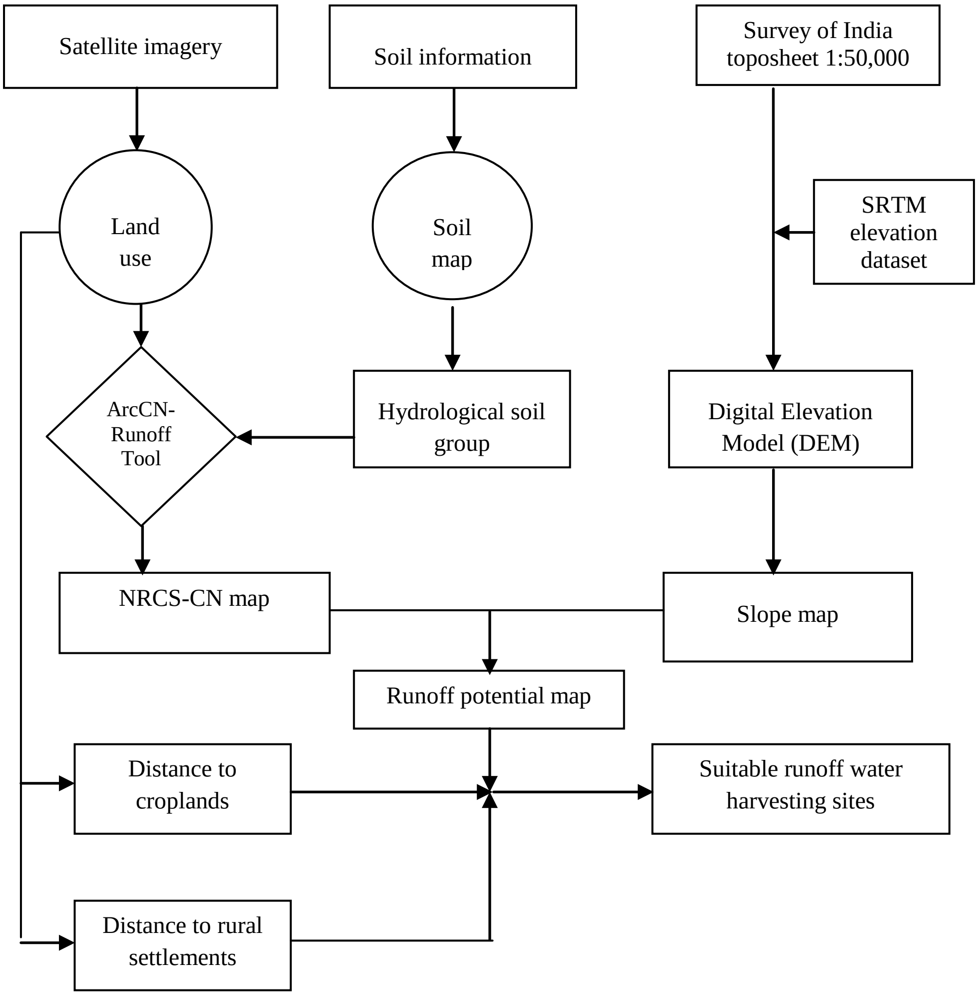

Fig. 2 Flow chart of methodology for deriving suitable runoff harvesting sites (modified from [3])

Data Sources

In this study, the input data required to characterise the necessary parameters (i.e. soil suitability, slope suitability, land use, harvesting potential for the upstream catchment and socio-economic parameters such as distance from croplands and settlements) were derived using available data as well as information obtained from field surveys. The Digital Elevation Model (DEM) was generated in ArcGIS 9.3 using 20 m contours from Survey of India toposheet on 1:50,000 scale and SRTM satellite data. Various land uses were identified and digitised from satellite data, followed up with ground truth mapping. The land uses were classified into following dominant land cover classes: forests, croplands, settlements, pastures/ scrubland, barren land and water bodies (Fig. 3). Based on the soil information (9) and field survey, textural classes were identified in the watershed as follows: sandy loam and clay loam.

Data Integration and Analysis

Input datasets were integrated and analysed using ArcGIS 9.3 for locating potential runoff zones and suitable sites for runoff harvesting. For this purpose, a number of Spatial Analyst tools available in ArcGIS were employed to solve various spatial problems, viz., calculating slope and distance, reclassification of values etc.

Slope: Hilly areas are significant in terms of rainfall-runoff response. The rapid runoff response from steep slopes results in non-availability of water in peak demand periods, even if the average rainfall is high. Slope is derived from a relief ratio, which is the ratio of the elevation difference between two points to the horizontal straight distance between the two points (10). Savna watershed consists of undulating topography. A slope map, expressed as percentage slope, for the Savna watershed was derived from the developed DEM in ArcGIS as illustrated in Fig. 4. For analytical purposes, slopes were grouped into four categories, viz., less than 2%, 2-3%, 3-6% and greater than 6% . Here, the mapping criteria adopted for locating potential runoff zones was steeper the slope, higher the potential runoff generation.

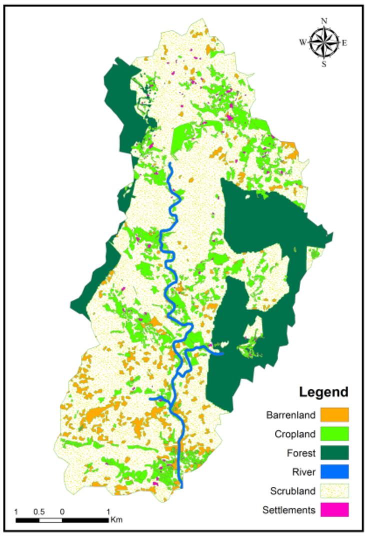

Fig. 3 Land use map for Savna watershed

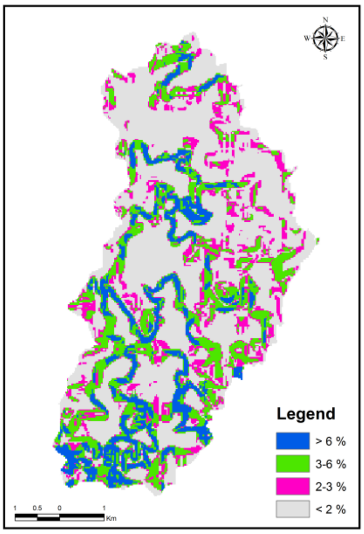

Fig. 4 Slope map derived from DEM

NRCS curve number: The NRCS method is the most common technique for estimating surface runoff for a given rainfall event. It considers the relationship between landcover (cover type, land treatment and hydrologic condition) and hydrologic soil group, which together constitute the curve number. A curve number is used to ascertain how much rainfall infiltrates into soil and how much rainfall becomes surface runoff; it is an index expressing a watershed's runoff response to a rainfall event. Curve numbers vary from 0 to 100 where greater curve numbers represent a greater proportion of surface runoff (11). Traditionally, an area weighted average curve number for the entire watershed is used to study the runoff of a watershed. The detail of spatial variation is often lost. This study takes help from GIS to produce curve number and runoff maps with the help of ArcCN-Runoff, a runoff tool available in ArcGIS (6). In ArcCN-Runoff tool, soil and land data are processed through the following three steps: (1) Soil and land use data for the watershed are clipped using a polygon feature such as the watershed boundary layer (2) Processing time is reduced by dissolving the soil and land use layers before intersection, based on the attributes 'hydrogroup' in soil and 'covername' in land use, (3) Soil and land use layers are intersected to generate new and smaller polygons associated with soil 'hydrogroup' and land use 'covername'. This step keeps all the details of the spatial variation of soil and land use, and can be taken to be more exact than using any average method to determine curve number (6). Employing the ArcCN-Runoff tool, the curve number for each polygon was determined from the soil and land use data for the Savna watershed. A map giving spatial variation of the curve number was generated as shown in Fig. 5 that was subsequently used to determine potential runoff zones.

Distance from cropland and settlements: Criteria used for identifying optimal sites for runoff harvesting should also include socio-economic aspects such as conveyance costs, distance from croplands and rural settlements. Longer the distance from croplands, the less suitable the area is for runoff harvesting because of the greater need for conveyance systems. The cropland and settlements were classified into five categories of varying distance intervals (refer Table 1). Depending on adopted criteria, each interval class for the cropland and settlement were allocated a suitability rank to facilitate the suitability analysis. Higher rankings represented areas of higher suitability for runoff harvesting. In general, there is a decrease in suitability with increasing distance from croplands and settlements with the exception of croplands having a low suitability (Table 1), since this land is valued more for cultivating crop instead of developing runoff harvesting systems.

Table 1 Suitability rankings for each distance interval class for rural settlements and crop lands (low rankings associated with a high suitability)

Interval class (straight line distance)	0 m	0–30 m	30–60 m	60–120 m	>120 m
Settlement ranking	1	2	3	4	5

Crop land ranking	4	1	2	3	5

POTENTIAL RUNOFF ZONES

Slope map and the NRCS curve number map were used to arrive at the runoff potential zones. In accordance with the slope-based criteria for surface runoff generation, the four slope categories were ranked from least suitable to most suitable with steeper the slope category, the higher the potential runoff generation. For the curve number map, higher curve numbers were indexed as potentially most suitable for runoff generation. The map of potential runoff zones derived from above parameters was a three-class qualitative grid map as shown in Fig. 6. The figure illustrates that a fair proportion of the Savna watershed has a medium to high potential to generate surface runoff during a rainfall event.

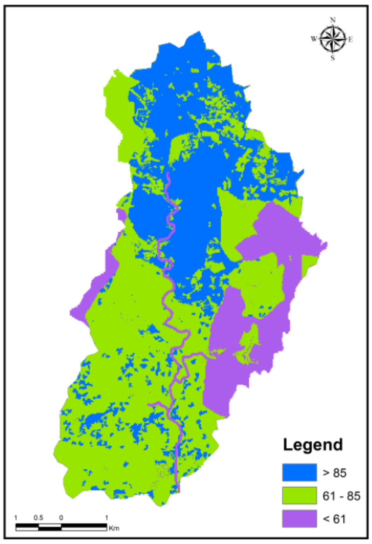

Fig. 5 Map showing the different curve number classes for Savna watershed.

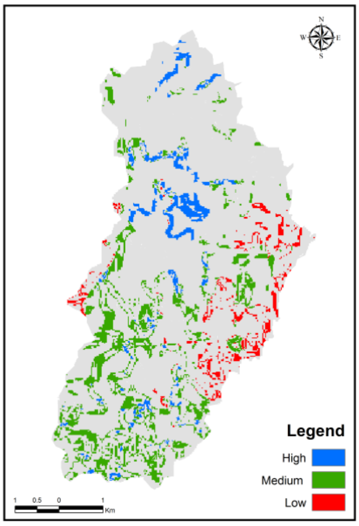

Fig. 6. Map of runoff potential zones for Savna watershed.

SUITABLE RUNOFF HARVESTING SITES

To identify the most suitable sites for runoff harvesting, suitability modeling was performed to create a single ranked map based on the potential runoff zones map and distance to croplands and settlements. The maps pertaining to socio-economic parameters consisting of five suitability rankings were combined with the runoff potential map comprising three suitability rankings. Combining these grid surfaces generated a map (refer Fig. 7) that indicates suitable zones, in terms of low to highly suitable, for harvesting surface runoff within the Savna watershed.

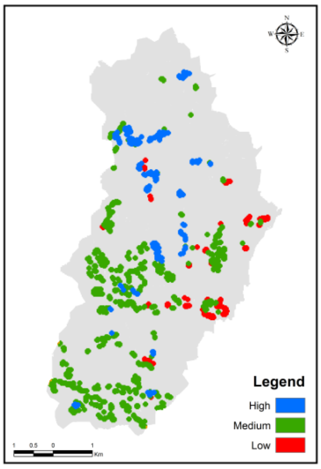

Fig. 7. Suitability map illustrating the low to highly suitable zones for runoff harvesting in Savna watershed.

CONCLUSION

In a water scarce rural watershed where the local community is dependent on rainfed agriculture, the ability to efficiently harvest the rainfall runoff is of vital importance to sustain agricultural production and reduce the community's vulnerability to water shortage. In this study, a GIS approach has been utilized for identification of suitable runoff harvesting sites in the Savna macrowatershed located in the semi-arid Jaisamand Lake Catchment. Based on integrated GIS modelling, 'suitability maps' have been developed for potential runoff harvesting sites. The GIS approach for locating suitable sites for runoff harvesting helps to reduce the extent of the area to be investigated for effective runoff harvesting, by identifying specific areas that are potential sites for runoff harvesting, and which can then be verified in the field. Providing an accurate spatial representation of the runoff generation potential within a watershed is an important factor in developing a strategic runoff harvesting plan for any water scarce rural watershed. The use of GIS approach to facilitate this process improves the accuracy level for locating suitable areas for runoff harvesting in view of the GIS capability to utilize spatial information in an integrative manner and spatially displaying it through maps.

Acknowledgments: The authors are thankful to Shri Rajan Vatsa, Scientist, NIH Roorkee, and Wells for India, a development organization in Udaipur for their support and for providing necessary field data.

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Dr. Anupma Sharma obtained a Ph.D. in Hydrology from the University of Roorkee in 1997. From 1998 she has been working as a Scientist in the Groundwater Hydrology Division at the National Institute of Hydrology, Roorkee, where she specializes in numerical groundwater flow and contaminant transport modeling, saltwater intrusion in coastal aquifers, and water harvesting techniques.

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