Journal of Rural Development, Vol. 37, No. (2), pp. 195-206
NIRD&PR, Hyderabad.

APPLICATION OF GIS AND MCE TECHNIQUES FOR OPTIMUM SITE SELECTION FOR WATER HARVESTING STRUCTURES

Arjita Saxena, Mahesh K. Jat*
and
*Sudhir Kumar***

ABSTRACT

Water is a primary necessity for the sustainable survival of all forms of life and enormously scarce in arid parts of the world including India. The basic unit of water resources assessment and planning is a watershed. Water resources management at a watershed scale requires both water supply and demand management which includes water conservation through rainwater harvesting, groundwater recharge, and recycling. The present study is aimed to assess the potential of water harvesting and to identify suitable sites for water harvesting structures in Kolayat watershed of Bikaner district in Rajasthan by using Geographic Information System (GIS) and Multi-Criteria Evaluation (MCE). Proposed methodology of water harvesting site selection has compared with traditional methods of site selection. In traditional practices, the location of the structure is selected by visiting the geographical areas and looking at the various drainage patterns, soil erosion, land use land cover, water storage areas, availability of insects/animals, native population feedback and past experiences. These practices are entirely dependent on instincts and results of the selected zones are uncertain. However, geospatial analysis techniques like RS, GIS, and MCE are the innovative tools which can be used to determine suitable sites for rainwater harvesting structures based on the watershed characteristics. The soil conservation service model (NRCS curve number) has been used to estimate the runoff. Further, spatial analysis in GIS has been carried out considering MCE along with the Analytical Hierarchy Processes (AHP) to assess the water harvesting potential and to identify the optimum locations of rainwater harvesting structures.

Keywords: Water Harvesting Structures, Geographic Information System, Precipitation, Catchment, Topography, Multi-Criteria Evaluation.

* Research Scholar and Faculty, Respectively, Civil Engineering Department, Malaviya National Institute of Technology, Jaipur-302017. INDIA E-mail: 2016rce9537@mnit.ac.in

Introduction

India is a developing nation with overall 2.4 per cent world geographical area, but irrespective of that it contributes 16.5 per cent of overall world population, has only 4 per cent of its renewable water resources (Nelson et al., 2009).Such a limited resource in the scenario of increased water demands from the ever-increasing population is a big reason for concern especially in arid and semi-arid areas like Rajasthan in India. Rajasthan holds the most extensive geographical area which is around 10.5 per cent of whole nation area, however, contains only 1.15 per cent (Kumar et al., 2013; Narain et al., 2006) of the total available water resources. Water plays a vital role not only in satisfying the basic human need for life and health but in socio-economic development also. Meanwhile, as the modernisation expanding its wings with the face of industrialisation, urbanisation and the importance of this finite natural resources is undervalued which results into over-exploitation of the water resource. To compete with the ever-increasing population, food production has to increase simultaneously with effective irrigation techniques. Optimum and efficient use of ground and surface water is the best way of water management practice to cope up with the water stress in the field of irrigation. Its production, as well as demand underground water level, is sinking is the typical scenario of Rajasthan nowadays due to over-exploitation and improper natural recharge, and due to this irregularity in the groundwater recharge natural hazardous situation is prevailing in the areas of annual rainfall below 50-60 cm.

Over the years water management practices in India and most of the developing countries includes supply management where supply is augmented with an increase in demands, which is not feasible in water scarce areas. From many studies, it is well established that for sustainable water resources demand management practices should be adopted along with supply management. Demand management can be categorised into (1) wastewater recycling; (2) altering the nature of the work so it can be accomplished with fewer water use (3) reducing losses in drive from sources through use of disposal; (4) shifting time of use to off-peak periods; and (5) increasing the productivity of the system to work (Brooks, 2006; Pingale et al., 2014; Singh et al., 2009). Different water demand management techniques are water conservation through rainwater harvesting and groundwater recharge, grey water recycling, increasing awareness, differential water tariff system, etc.

From past several years human being is developing various methods to conserve water which is somehow not serving the problem as that technique is traditional, judged and adopted from past skills of precipitation movement, drainage patterns, soil erosion, forest/crop cover, water storage areas, availability of insects/animals, native population feedback in watershed area. In recent past, new technologies have been developed to overcome shortcoming of traditional methods of water conservation like remote sensing, GIS and MCDM which is used to for accurate estimation of runoff produced from catchments, incorporating the spatial and temporal variations of catchment characteristics in resources estimation and making more informed decisions about selection of appropriate water conservation measures and sites of their implementation.Geospatial technologies like RS and Geographical Information System (GIS) are very efficient in capturing of watershed characteristics, bringing diverse data from different sources to a universal standard and analysing hydrological processing for making optimum decisions related to water conservation. Now a selection of water conservation structures, determination of their capacities and location are being assessed on the ground based on technical parameters like the slope of the land, contour lines, surface characteristics, surface & sub-surface drainage pattern, infiltration rate.

In recent years, new technologies have been proposed such as integration of MCE & GIS technology.This modern technique made work easy and accurate for best site selection of watershed intervention works (Tsiko and Haile, 2011). But still, efforts are needed to get the broader insight of such methods which were introduced in 1960 for supporting in decision – making.This method is dominantly accepted in the watershed development field. The spatial decision support system (SDSS) is the integral part of GIS and MCE for assessing the suitable site for a variety of facilities and works (Tsiko and Haile, 2011). The analytic hierarchy process (AHP) is based on multiple criteria decision-making theory which combines spatial analysis functions of the GIS (Yalcin, 2008) in the selection of WHS producing suitability maps. AHP is an organised method which gives proper decisions for site selection.

Rainwater harvesting is an ancient technique of collecting water from the roof, construct catchment and delivering the collected rainwater to a storage tank for domestic use after treating with the proper filtration mechanism.The water so collected from the roof or catchment can be used in different ways like for domestic purpose or for groundwater recharge. For an optimum collection of rainwater, proper site selection is the primary criteriaon which can only be achieved after the data available for the installing of RWH that can be supplied by modern techniques such as remote sensing and GIS techniques (Kumar et al., 2008).Each watershed has various physiographic characteristics such as geomorphology, geology, structures, land use/ land cover (LULC), soil and drainage pattern needs to be captured through remote sensing and processed in GIS for optimum site selection of appropriate water harvesting structures.

Therefore, present study is aimed to assess the potential of water harvesting and to point out the best site for watershed development activity in Kolayat watershed of Bikaner district in Rajasthan by implementing modern methods of GIS and Multi-Criteria Evaluation (MCE).

Study Area and Data Used

In the present study, Kolayat watershed in Bikaner district in Rajasthan State has been chosen as the study area. As per GIS, total catchment area of the Watershed is 793546 ha. The geographical location map of the watershed is shown in Figure 1.The watershed area extends between latitude 28.394 N and 27.382 N and longitudes 71.883 E and 73.189 E. The agro-climatic condition of watershed area is under the arid reason and extreme condition of temperature in summer as well as in winters whereas monsoon is of shorter period. The maximum average annual rainfall within the watershed is 250 mm, and the maximum average annual temperature is 28-49°C. As per Census 2011, Kolayat's population is 9684(IWMP KOLAYAT et al., 2010-11).

The watershed area has a maximum elevation of 319 m. The watershed area has mixed topography i.e. plain as well as undulating. The latest drainage channel network has been made by satellite data. The drainage pattern of watershed area follows dendritic and sub-dendritic. Roads and settlement layers have been derived from Satellite Data. Kolayat Watershed is a part of Bikaner district.

To achieve the study objectives, a variety of data/information are required to be collected from various, sources.

1. Landsat 8 images, band 3, 4, 5; Resolution – 30 meters.
2. SRTM DEM, Resolution – 30 meters.
3. Rainfall data of 16 years (2000-2016).
4. Toposheet (1:25000).

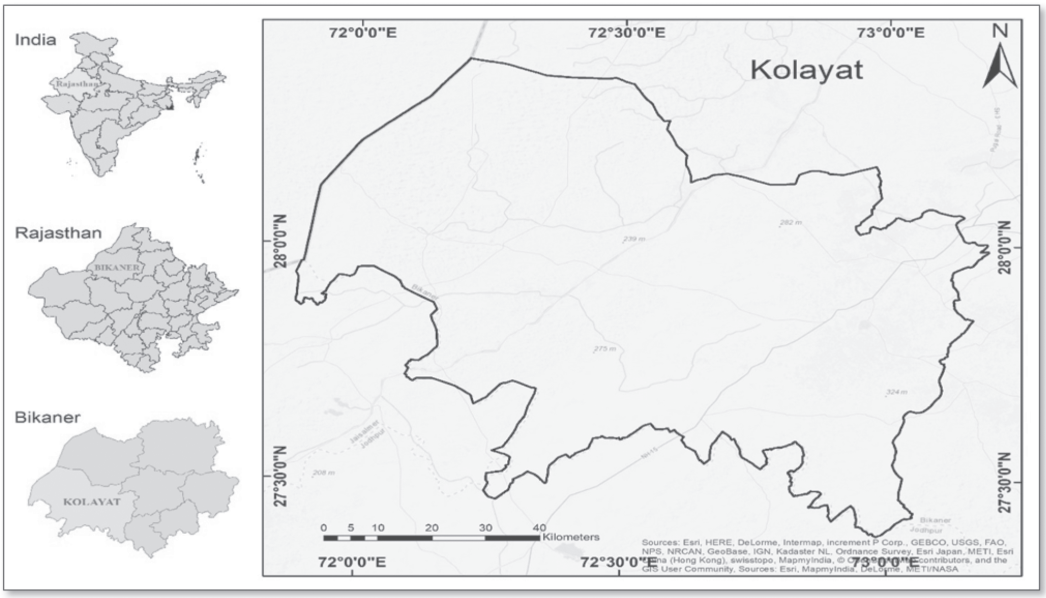

Figure 1: Study Area

Methodology

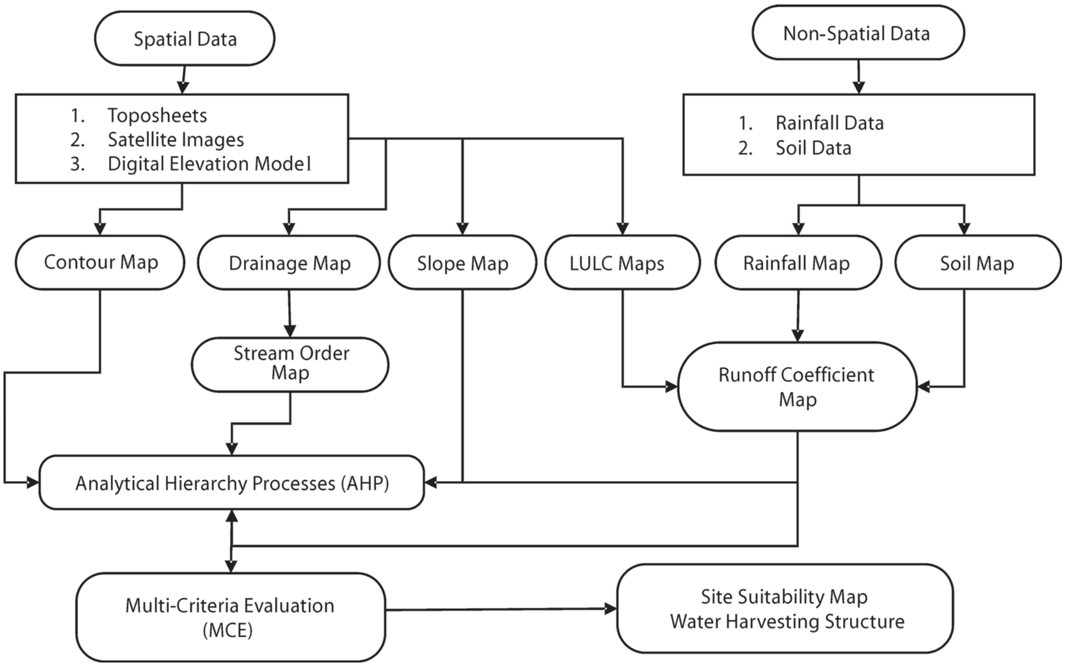

Figure 2: Methodology Flow Chart

To determine the suitable locations of possible water harvesting structures, first of all runoff potential has been determined using NRSC-CN method. Rainfall-runoff modelling has been done in GIS. For the rainfall-runoff modelling, required input parameters have been extracted from GIS database created for the catchment characteristics. Created thematic layers in GIS include LULC map, soil map, drainage map, DEM, slope map. To create the GIS database different types of spatial data which include toposheet, satellite image, and digital elevation model are used in addition to non-spatial data like rainfall data. LULC information was extracted from classified satellite images. Further, NRSC-CN method has been implemented in GIS to determine the runoff to be generated from the catchment to assess the available runoff for harvesting. Then all maps are categorised in the range of 1 to 9 by the technical parameter of water harvesting structure using AHP technique. After this process, multi-criteria evaluation method has been used to determine the best suitable site for water harvesting structure. The detailed methodology has been presented in Figure 2.

Slope and Contour: The topography of watershed area can be studied by slope data and for generating a slope and contour map Digital Elevation Model (DEM) is required. A contour map is used to delineating water harvesting structure, i.e.Continuous Contour Trench (CCT),a Staggered Trench (SGT),Deep Continuous Contour Trench (DCCT) and waste weir of different structures. The time of concentration and peak runoff rate of the watershed area is directly dependent on the average slope of the particular area. Slope map characterises classes such as 0-1%, 1-3%,3-5%,5-8%,8-15% and >15%.

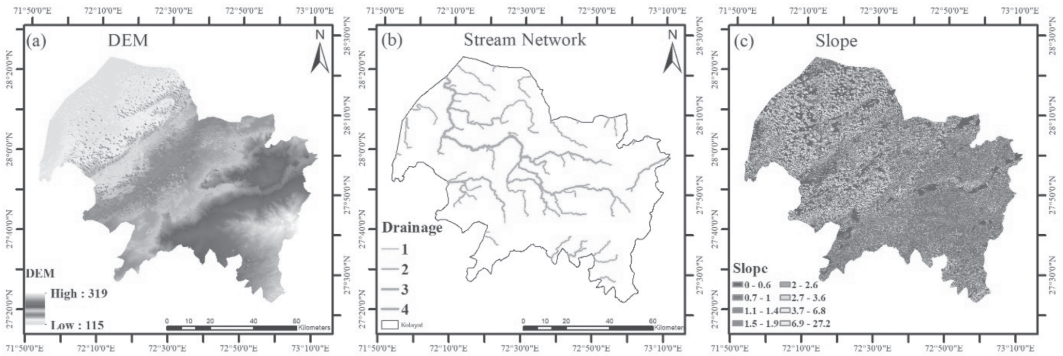

Figure 3: (a) DEM Map, (b) Stream Order Map and (c) Slope Map

Drainage and Stream Order: Drainage line has been used to delineate the catchment of watershed and it also gives assistance in suggesting various WHS locations.The drainage pattern is formed by the grouping of streams, rivers, and lakes in a drainage basin. In a drainage system, streams and rivers connect each other in the form of a network. In the modern technique of GIS, this network is seen as irregular line segments which contain geographical coordinates and topological relationship. After drainage delineation, stream orders are assigned to each tributary,and sub-tributary respectively. Stream order is a positive integer number to indicate the level of branching in a river system. The smallest tributaries are called first order streams, while the largest river is referred as a consecutive largest number. Drainage order has been representing the number of drains present in each order defined, i.e. 1, 2,3,4,5 and 6 stream orders.

Soil: Texture gives an idea about the relative content of elements of various sizes, such as percentage of sand, silt, and clay in the sample of soil. Soil texture is a major criterion for selecting water harvesting structure site. The watershed area comprises a range of soil texture from fine loamy to sandy loamy and rock outcrops. (Daniels, 2016). Hydrology Soil Group map is also prepared by analysing soil group map and this map is categorised into four classes i.e. A, B, C, D.

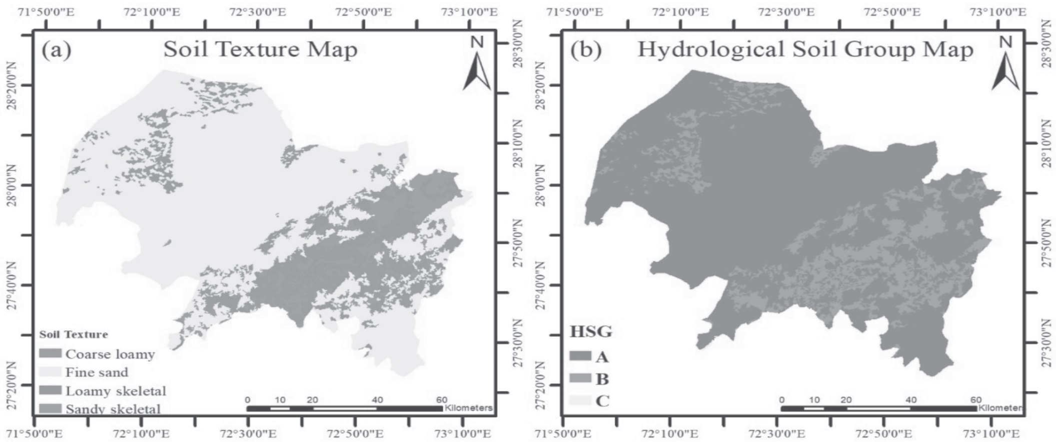

Figure 4: (a) Soil Texture Map and (b) Hydrological Soil Group Map

Land Use Land Cover (LULC): ERDAS Image software has been used to identify the pattern of land use land cover from satellite image. For different classes of LULC, training samples have been selected to collect the signature for supervised classification. In a supervised classification, perimetric and maximum likelihood method is used.The classified image consists of different types of LULC classes such as agriculture land, rock land, scrub land, water bodies and urban (Built-up).

The land use land cover pattern gives a significant effect on peak rate of runoff volume. An area with dense forest cover, acts as a barrier to the water flowing velocity which results into a little surface runoff and gives enough time for water to settle down a bit, due to the fact that more rainwater is absorbed by the soil.

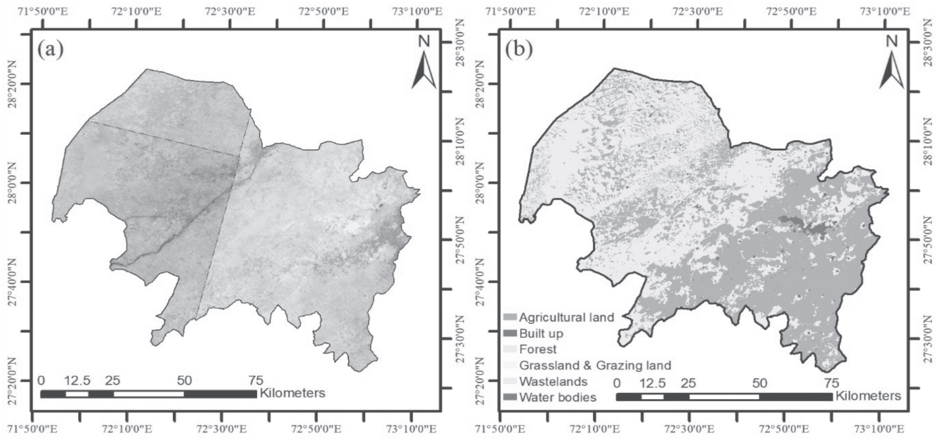

Figure 5: (a) Satellite Image and (b) Land Use Land Cover Map

Rainfall Data : Rainfall data of past 16 (2000-2016) years have been used to analyse the rainfall pattern in the study area that includes the type of precipitation, rainfall intensity, duration of rainfall and rainfall distribution.It has been observed that highest rainfall has occurred in 2003, 2011 and 2015 during past 16 years of rainfall record.The overall trend of rainfall is slightly decreasing which is shown in Figure 6.

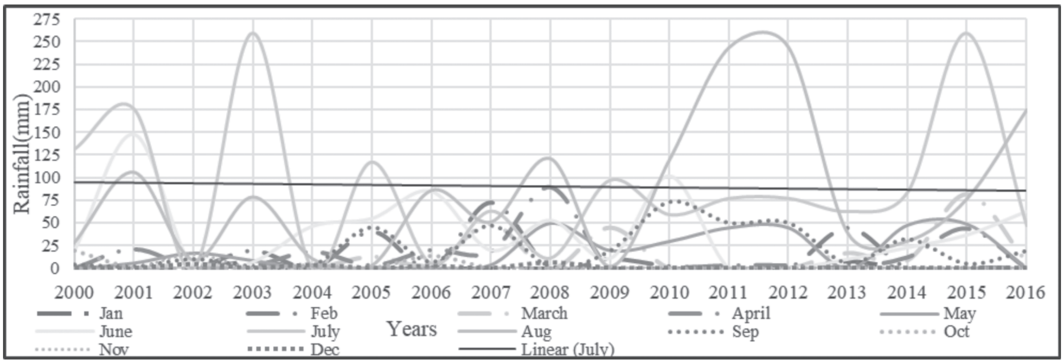

Figure 6 : Total Monthly Rainfall (mm) at Bikaner Station

Runoff Coefficient (C): Runoff coefficient, expresses the view about the fraction of rainfall resulting in surface runoff. It may be defined as the ratio of runoff and rainfall. Values of runoff coefficient are assigned by land use and soil types using NRCS-CN approach. In Figure 6, the runoff coefficient values vary from zero to one. A low value indicates most of the water which falls stayed on the ground surface and infiltrated into the ground, whereas the high value shows the reverse phenomenon i.e. flow away from the watershed rapidly.

Analytic Hierarchy Process and Multiple Criteria Decision-Making : The AHP is an eigenvalue technique to the pair-wise comparisons approach. It provides a numerical fundamental scale, which ranges from 1 to 9 to calibrate the quantitative and qualitative performances of WHS (Uyan, 2013). AHP weights are calculated by weightage criteria in Arc GIS software. The weightage reflects the relative importance of each criterion.The principles utilised in AHP to solve problems are to construct hierarchies. The hierarchy allows for the assessment of the contribution individual criterion at lower levels make to criterion at higher levels of the hierarchy (Chandio et al., 2013). After giving the weightage of each parameter, computations performed to find the maximum eigenvalue (λmax), consistency index, consistency ratio (CR), and normalised values for each criterion.

Consistency index (CI):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

Where n is the number of items being compared.

Consistency Ratio (CR):

$$CR = \frac{CI}{RI} \quad (2)$$

Where RI is the random index, which is the consistency index of a randomly generated pair-wise comparison matrix. It can be shown that RI depends on the number of elements being compared and takes on the following values.

Results

To determine the best suitable location for RWH, decision rules have been formed on the information available in the literature and technical reports of integrated watershed management programme (IWMP).The details of the decision rules have been shown in Table 1. The required check dam design should provide up 3rd order drainage; catchment area should be 4 hectares or more and slope should be less than 10 per cent for all other structures selecting criteria are shown in Table 1.These decision rules have been used in AHP and MCDA.

The 0-3 per cent class slope is suitable for following actives, i.e. field bundling, khadin, percolation tank and sub-surface barrier.The 3-8 per cent class slope is suitable for following actives, i.e. LSCD, MPT, and ECD.The >8 per cent class slope is suitable for actives such as gradoni and CCT, DCCT, V Ditch, Staggered trench.

The stream order of 1st 2nd and 3rd are favourable sites for farm pond , ini percolation tanks (MPT) and check dams whereas 3rd and 4th order streams are for mini irrigation tanks (MIT) The structures for water harvesting like field contour bunding are done on contour lines with a land slope less than 4 per cent irrespective of size, the shape of the land, whereas, in the case of CCT, DEEP CCT, V – Ditch slope of land need to be between 5 to 15 per cent. Gabion is constructed on afforestation land with a slope more than 20 per cent with good soil depth. Structures like MPT drainage lines and their slopes are being considered for its construction i.e. 2nd or 3rd order drains are considered for MPT construction and 4th order is pointed for MST only. The multi-layer combination through LULC, slope, soil (HSG), stream order and settlement gave the suitability sites for identifying the water storage structures.These layers were processed in Arc GIS using weighted overlay analysis. So different structures need different technical parameters for implementation of those structures in the watershed area for efficient performance.

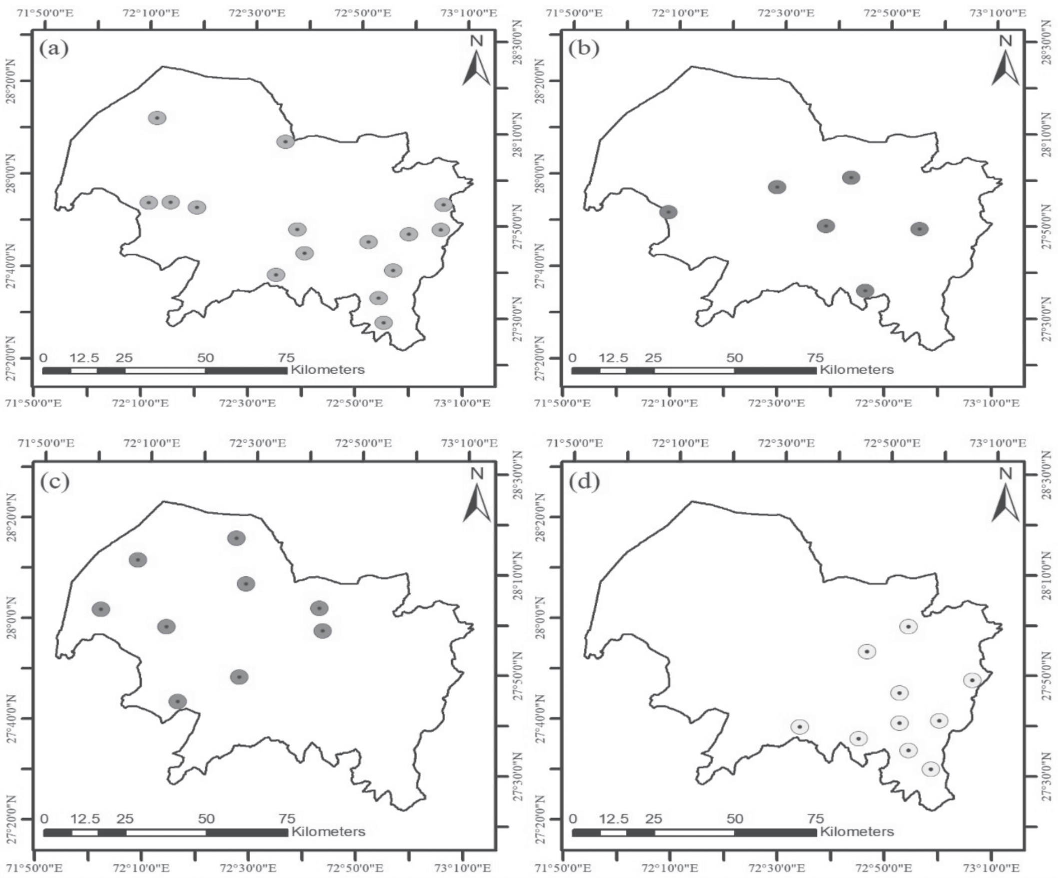

Figure 7: Suitability Map for WHS in the Study Area (a) Farm Pond (b) MPT (c) Percolation Tank and (d) Khadin

Table 1 : Decision Rules for the Selection of Suitable Locations for the Various Rainwater Harvesting Structures

Type of structure	Slope	LULC	Drainage	Other conditions
Check dam	<10%	River/stream near agriculture land	Up to 3rd order	Catchment 4 ha or more
Percolation tank	0-3%	Open land drainage course	2nd & 3rd order	Adjacent to precentral stream fractured zone
Underground barrier	0-3%	River bed	4 to 7 order	Enough river bed thickness 5m or more
Farm pond	1-3%	Agriculture land	1 & 2 order	Sufficient water stream bed
Contour field bund	1-3%	Agriculture land	1st order	
CCT	5-8%	Sloppy terrain		Enough slope for water to flow
V ditch	5-15%	Sloppy terrain		Enough slope for water to flow
Gradoni	Up to 20%	Sloppy terrain		High flow intensity
Khadin	1-3%	Agriculture land		Low rainfall area less than 100 mm

Conclusion

In the present study, application of geo-spatial technologies i.e., remote sensing and GIS and multi-criteria analysis techniques have been demonstrated in selecting the optimum water harvesting sites. Runoff potential has been determined for the area using NRSC-CN method, which was implemented in GIS using catchment and meteorological characteristics of the area. Further, AHP approach was used to assign weightages to the different variables suitable for selection of water harvesting structures. Further MCE has been used in GIS to determine suitable sites of water harvesting structures.Total 48 sites have been selected in the present study for the Kolayat watershed in Bikaner district. Integration of remote sensing techniques and GIS can provide an appropriate platform for analysis of multi-disciplinary data and sustainable development of land and water resources.

To make rural areas water sustainable, efficient use of available water and their conservation is essential in a scenario of water increasing demand. It is very critical for arid and semi-arid areas. It is a well-established water demand management through rainwater harvesting, soil moisture conservation, groundwater recharge, reuse of marginal water.

The derived estimation runoff, considering a temporal and spatial variation of catchment characteristics in the rural areas where water resources such as rainwater harvesting, groundwater recharge, soil moisture conservation are important development works of sustainable livelihood and natural resources.

This paper presents an application of geospatial technologies for correctly estimating the available runoff of rainwater harvesting, groundwater recharge potential and selection of an optimum location for such intervention works which is very useful for sustainable rural development.

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