Chapter 1
GIS-Based Multi-criteria Decision Analysis for Identifying Rainwater Harvesting Structures Sites in a Semiarid River Basin

Pawan S. Wable, Madan K. Jha, V. M. Chowdary, and Smaranika Mahapatra

Abstract The current study was accomplished in a drought-prone semiarid basin of Maharashtra with the objectives of assessing rainwater harvesting (RWH) in potential sites and identifying the most appropriate sites for RWH and artificial recharge structures. The analysis was performed using remote sensing, GIS, and multi-criteria decision analysis (MCDA). The thematic layers, i.e., land slope, drainage density, and runoff coefficient of the normal years, were used to develop the RWH potential map. Saaty's scale was used to assign suitable weights to the thematic layers and their respective features, and then they were normalized by utilizing the analytic hierarchy process-based MCDA technique. In addition, the suitable sites for the RWH and recharge structures were identified using desirable criteria and Boolean logic, and later sites were prioritized for their cost-effective implementation based on socio-hydrological conditions. The results revealed that 80% of the study area is dominated by zones with "moderate" RWH potential in "normal" years. Moreover, 35% of the study area is suitable for the farm ponds, whereas 2% each for check dam and percolation tanks. For the cost-effective implementation of

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proposed RWH structures, 11% of the agricultural area is prioritized for the excavation of farm ponds, and 284 sites are prioritized for the construction of check dams.

Keywords Multi-criteria decision analysis · SCS curve number method · Geospatial techniques · Rainwater harvesting · Zone prioritization

1 Introduction

Development of any area primarily depends on water availability as it plays an important role in social, economic, and environmental dimensions. Agriculture, domestic, and industrial sectors are the major water-demanding sectors. Among them, economy-wise agriculture is the most responsive to water scarcity as it accounts for 70% of global freshwater use and not less than 90% of the consumptive use (FAO, 2012). By 2050, it is projected that 60% more food will be required to fulfill the demand of a concluding population of 9 billion. In many areas, currently, water scarcity has severely limited food production, thereby threatening food security. Rainfed agriculture is the prime source of food grains in the world. India with 60% total land area under rainfed area ranks first, and All India Report on Agriculture Census 2010–2011 (2015) highlights that India's 89% millet, 88% pulses, and 73% cotton production come from rainfed agriculture, and it supports 72% of total livestock. However, these areas are characterized by land degradation, poverty, malnutrition, water scarcity, climate variability, crop failure, and a lowest average productivity of less than 1 t/ha (Rockstrom et al., 2010). In addition, these regions also experienced droughts every 3-year cycle (DTE, 2015). On the other hand, the remaining 40% of India's total land area is irrigated land that helps to serve 55% food requirements of the country. However, it consumes 70% of the freshwater resources and provides less scope to extend it further (CWC, 2005). Even though with the implementation of the best scenario of irrigation development, Parthasarathy Committee (2006) estimated that about 40% more supply of food grains would be needed from rainfed agriculture to fulfill increased future demand. Hence, revolution is vital in rainfed agriculture for food security as well as mitigating poverty and malnutrition in India.

Nowadays, among the several solutions available for mitigating the impacts of droughts, rainwater harvesting (RWH) has emerged as the most effective solution for water conservation and groundwater augmentation. This is due to fact that rainwater is easy to collect and a reliable resource for domestic and agricultural use without any treatment. RWH is gaining popularity as they ensure the availability of fresh and safe water when the common source of water fails. Besides that, the conserved surplus monsoon runoff can be used for underlying aquifers, thereby artificially augmenting depleting groundwater resources. The RWH can be achieved by both in situ and ex situ interventions (Kahinda & Taigbenu, 2011; Wani et al., 2011). In situ interventions are performed in farmer's fields to conserve the rainwater in the form of soil moisture, e.g., field bunding, broad bed and furrow practices, etc. Ex situ interventions are structures constructed outside the fields, e.g., farm ponds, check dams, and percolation tanks with storage capacities ranging from 100 to

5000 m^3. Among them, the cost of ex situ interventions is much higher than in situ interventions. Furthermore, ample government funds are assigned to numerous rural development and employment schemes through which the construction and maintenance of different ex situ interventions are executed at a basin scale. Hence, the decision for the selection of the RWH sites for ex situ interventions is very important.

Successful implementation of RWH and artificial recharge structures in any area depends mainly on the runoff potential of the area and the identification of suitable sites for constructing these structures. According to FAO (2003), six main parameters should be studied for selecting RWH sites: rainfall, runoff, terrain slope, crop characteristics, physical properties of soil, and socio-economic conditions. The rapid progress in geospatial techniques has served as a valuable tool for effective decision-making planning and management of natural resources at a larger scale. It facilitates an effective and user-friendly analysis of the spatiotemporal data (FAO, 2003). Few of its applications are the evaluation of groundwater prospect, runoff potential, RWH potential, zoning of waterlogged/salt-affected areas, recharge-discharge areas, etc. The RWH has been practiced in semiarid/arid regions of India (Sahoo, 2004; Ramakrishnan et al., 2008; Jasrotia et al., 2009; Bamne et al., 2014), Jordan (Ziadat et al., 2012), Iran (Ghayoumian et al., 2007), West Asia and North Africa (Oweis et al., 1998), etc. In these studies, thematic layers derived mainly were slope, drainage, land use, and surface runoff. For the Indian regions, the suitability criteria for RWH sites in most studies were based on the guidelines of the Integrated Mission for Sustainable Development (Ramakrishnan et al., 2008; Jasrotia et al., 2009; Bamne et al., 2014). For RWH planning, the important component surface runoff was estimated using either Soil Conservation Service Curve Number (SCS-CN) method (Sahoo, 2004; Ramakrishnan et al., 2008; Kadam et al., 2012) or Thornthwaite-Mather method (Jasrotia et al., 2009) with former one being widely used. Ramakrishnan et al. (2008) conducted a field survey to validate recommended sites for RWH structures that indicated 80–100% accuracy. A different study by Ziadat et al. (2012) demonstrated a methodology to identify suitable RWH structures using a participatory GIS approach that combines social, economic, and biophysical criteria.

In the RWH planning for large areas, multiple factors were often conflicting, e.g., different soil types, slope classes and land use/land cover (LULC), drainage density, runoff classes, etc. GIS-based multi-criteria decision analysis (MCDA) and Boolean logic can deal with this problem, which constitutes a powerful framework (Voogd, 1983; Malczewski, 1999). Hence, in the recent past, the combination of multi-criteria decision analysis (MCDA) along with geospatial techniques has attracted several researchers for the evaluation and identification of potential RWH potential and artificial recharge sites (Chowdhury et al., 2010; Weerasinghe et al., 2011; Jha et al., 2014; Mahmoud et al., 2016; Singh et al., 2017). In most of these studies, the analytic hierarchy process (AHP)-based multi-criteria decision analysis technique was used to assign different weights to the thematic layers according to their importance. They were combined using the weighted linear combination method to generate RWH potential maps. Weerasinghe et al. (2011) developed the Geographic Water Management Potential (GWAMP) model, which was tested and validated in Sao Francisco and Nile catchments with different geographic and climatic conditions. They concluded that in a given catchment, the GWAMP model could be used for identifying RWH potential sites. Mahmoud et al. (2016) presented a methodology for managing agricultural drought in arid and semiarid regions by RWH in El Beheira Governorate, Egypt. The agricultural drought was monitored using the NDVI differencing technique. For drought management, the developed RWP map was categorized into suitable and unsuitable classes. In another study, Singh et al. (2017), for the realistic implementation of the RWH and artificial structures in Damodar canal command of West Bengal, India, prioritized the identified zones by considering some key factors like groundwater level during the post-monsoon season, groundwater fluctuation, and spatial water demand. Recently, Toosi et al. (2020) presented a realistic method to identify probable RWH areas using the GIS-based MCDA technique and to consider socio-economic factors at a basin scale in northeast Iran. The study revealed that 52% of the study area was appropriate for various RWH structures.

A review of the above pertinent literature suggests that several studies have reported using RS- and GIS-based MCDA for the RWH potential zoning. However, prioritization of sites for RWH and artificial recharge structures for cost-effective implementation of the RWH plan by considering socio-hydrological factors is not common, although it is very helpful for water management decision-makers. With these facts and issues, this study was done in an agriculture-dominated drought-affected semiarid climate-characterized river basin of Western India (Wable et al., 2018). The objectives of this study are (i) to identify RWH potential zones using GIS-based MCDA, (ii) to identify suitable sites for the different RWH structures, and (iii) to prioritize the selected RWH structures for their cost-effective implementation. In this study, specific thematic layers like post-monsoon groundwater level, irrigation command area under major/medium projects, and proximity of rural settlements are considered for prioritizing zones/sites for the construction of RWH and artificial recharge structures. The study presents a one-of-a-kind practical approach for identifying the best suitable RWH sites and artificial recharge structures, which can be easily adopted by the policymakers and water managers of any area.

2 Material and Methods

2.1 Overview of Study Area

The present study was carried out in the semi-urban Sina River basin. The location of the study area is confined between 17° 28′ N and 19° 16′ N latitude and 74° 28′ E and 76° 7′ E longitude. The area covers 12,244 km^2 in Western India (Fig. 1.1). The basin falls into four districts, namely, Solapur, Osmanabad, Ahmednagar, and Beed, with the major portion (42%) of the basin coming under the Solapur district. The

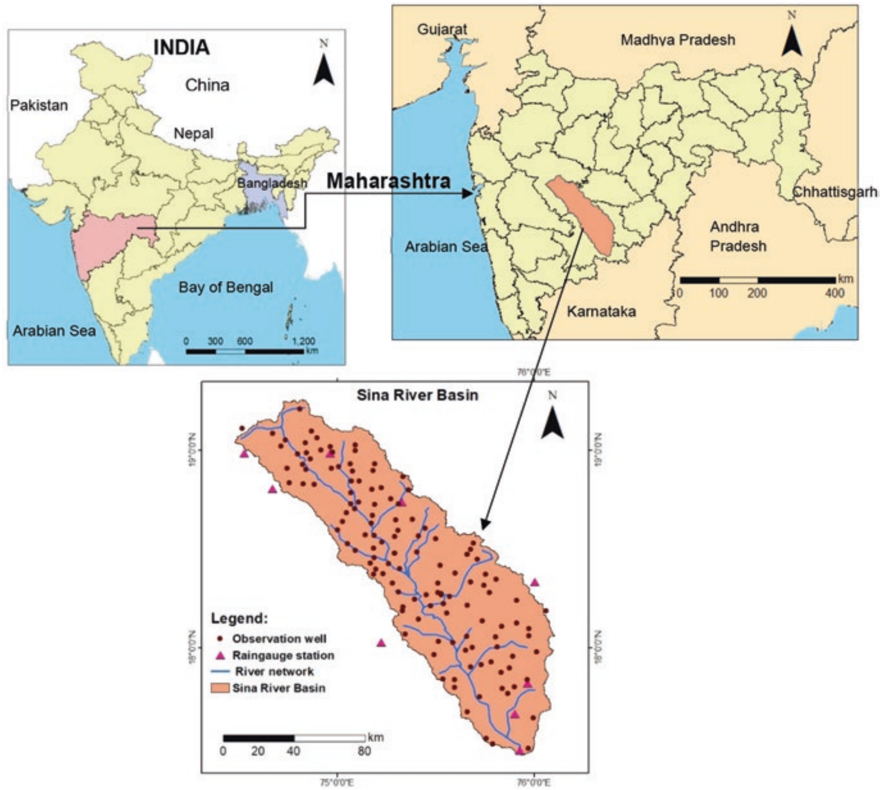


Fig. 1.1 Study area map showing the locations of hydrometeorological monitoring sites

elevation ranges between 420 and 964 m above MSL. The climate of the river basin is characterized as semiarid. The average annual rainfall of the study area is 644 mm, with most rainfall falling during the monsoon season (June–October). In the study area, the majority of the part (80%) is covered by agricultural use in which both type monsoon (*Kharif*) and non-monsoon (*Rabi*) season crops are grown. The main crops grown are fodder grass, groundnut, pearl millet, pulses, safflower, sorghum, sugarcane, wheat, and various other horticultural crops. Sugarcane is the major cash crop, which is mainly cultivated in the assured irrigated area of the region. Agriculture, hydropower, industries, and drinking demands are the main consumers, with agriculture sharing the largest among all. The main sources of irrigation in the study area are canals and/or groundwater. However, groundwater fulfills more than half of the irrigation water requirement in the catchment. Hard rock underlies the basin with an unconfined aquifer at shallow depth (up to 20 m), while semi-confined and confined aquifers prevail at deeper depths. The thickness of the unconfined aquifer over the area varies from 5 to 20 m (MoWR & CGWB, 2013). Groundwater is generally extracted from dug wells or dug-cum-bore wells, which tap water from the upper portions of weathered or fractured Deccan basalt. The surface water source of irrigation in the study area is carried out with one major, 20 medium, and several minor irrigation projects.

2.2 Data Acquisition

Daily rainfall data for the period 1985–2009 were collected for nine rain gauge stations from the State Data Storage Center, Hydrology Project (HP), Nashik, India, and India Meteorology Department (IMD), Pune. The land use/land cover map (scale 1:50000) was collected from the National Remote Sensing Center (NRSC), Hyderabad, India. The soil map of the study area (scale 1:250000) and the related soil physical and hydraulic characteristics were acquired from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), Nagpur, India. The SRTM digital elevation model of grid size 90 m was downloaded from the CGIAR Consortium for Spatial Information website (Jarvis et al., 2008). In addition, the post-monsoon groundwater level data of 132 wells (1985–2009) were procured from the Groundwater Survey and Development Agency (GSDA), Pune, India.

2.3 Extraction of Thematic Layers

Rainwater harvesting (RWH) mainly depends upon the threshold value of rainfall, a prime factor that generates runoff. Also, catchment types (with different soil conditions and land use/cover) and catchment characteristics like slope, drainage density, etc. play a crucial role in evaluating the potential of an area for harvesting rainwater and identifying the suitable sites of harvesting structures, which makes it as a complex multi-criteria problem. In this study, the RWH potential map was generated using the basic and derived thematic layers, e.g., runoff coefficient, slope, and drainage density, as recommended by Jha et al. (2014). Rainfall maps were generated using the daily rainfall data for 25 years. The standard "Thiessen polygon" method was employed for quantifying the mean areal rainfall, which was further used for creating the rainfall map of the studied catchment (Singh, 1992; Subramanya, 2008). The soil map was again classified into hydrologic groups based on soil properties such as its texture and infiltration characteristics to obtain the soil hydrologic group map. Maps depicting spatial "runoff potential" and "runoff coefficient" over the basin were developed by considering rainfall, soil, and land use/cover information, which is illustrated in the next sections. The slope map and drainage density of the study area was extracted from DEM by using in-built algorithms in ArcGIS 10.1 software. For the drainage density map, first, the sub-watershed map and drainage network maps of the study area were prepared. Further, the drainage network map and the sub-watershed map were combined, and a drainage density map was prepared as a composite layer. In addition, some more thematic layers such as drainage network map, settlement map, irrigation command map, and post-monsoon water table map for the "normal" year were also prepared to identify the appropriate sites for RWH and artificial recharge structures.

2.3.1 Runoff Coefficient Map Preparation

The runoff coefficient is that part of total rainfall which directly contributes to the generation of runoff. Many previous studies used direct surface runoff estimation by the Soil Conservation Service Curve Number (SCS-CN) technique (SCS, 1985), a conceptual model developed by USDA, which has proven to provide accurate results in lack of runoff measurements areas (Al-Ghobari et al., 2020). Hence, this method was used in the current study to quantify direct surface runoff, i.e., runoff potential. For this, a distributed CN approach was applied in the GIS environment. Rainfall data, along with soil and LULC cover maps, were utilized for modeling runoff and generating runoff potential maps. The value of the initial abstraction ratio (λ) in the SCS-CN method, which generally ranges from 0.1 to 0.4 as found in different studies conducted in different geographic locations, was taken to be 0.3 in this study (Subramanya, 2008). Following standard guidelines, the antecedent moisture condition (AMC) was determined (Singh, 1992; Subramanya, 2008). The values of potential maximum retention (S) were calculated using the assigned distributed CN values for daily rainfall. Thiessen polygon method was used for computing the area coverage for each rain gauge station. After that, the estimated daily runoff values were converted to an annual scale, and the maps of runoff potential of the basin were prepared for three rainfall scenarios: wet, normal, and dry conditions for the years. It is to be noted that the wet year indicates that the year has higher rainfall than the average annual rainfall (AAR), while it is considered that the normal year was defined as a year when the total rainfall received was equal to the AAR. On the other hand, a year having annual rainfall less than or equal to 25% of the AAR was defined as a dry year (Subramanya, 2008). Further, runoff coefficient maps were created for the study area for all these three rainfall scenarios, i.e., wet, normal, and dry years, by dividing runoff by the corresponding rainfall year.

2.4 Multi-criteria Decision Analysis

The runoff coefficient map for the normal year and slope and drainage density maps were used for delineating RWH potential zones. Analytic hierarchy process (AHP), which is a multiple criteria decision-making tool (Saaty, 1980), was used for generating an RWH potential map for the study area. Based on the local experience and experts' notions, weights were allotted to the three thematic layers (i.e., runoff coefficient, drainage density, and land slope) and their features based on their relative effect on the RWH potential in the 1–9 scale (Saaty, 1980). Further, the eigenvector technique was applied for the normalization of these assigned weights. The consistency ratio (CR) was calculated to evaluate the consistency of the normalized weights as follows:

$$\text{Consistency ratio }(\text{CR})\frac{\lambda_{\max}-n}{n-1} \tag{1.1}$$

where $\lambda_{\max}$= principal eigenvector (obtained from eigenvector technique) and n = number of criteria or factors. To maintain consistency in the assigned weights, the CR should be less than 10% (Saaty, 1980); otherwise, assigned weights should be reassessed.

2.5 Development of Rainwater Harvesting Potential Map

The abovementioned thematic layers, viz., runoff coefficient, slope, and drainage density, along with their respective normalized weights, were combined by weighted linear combination (WLC) method using ArcGIS software, and thereafter, the Rainwater Harvesting Potential Index (RWHPI) was calculated to delineate RWH potential zones, as follows:

$$\text{RWHPI} = \left(\text{RC}_{\text{w}}\text{RC}_{\text{wi}} + \text{SL}_{\text{w}}\text{SL}_{\text{wi}} + \text{DD}_{\text{w}}\text{DD}_{\text{wi}}\right) \tag{1.2}$$

where RC = runoff coefficient; SL = slope; and DD = drainage density. The subscript “w” denotes the normalized weight of a theme, and “wi” represents the normalized weight of the individual features. The RWHPI is a unit less quantity that indicates the feasible RWH potential zones/sites in an area. Thus, the study area’s RWH potential map was generated for the “normal” rainfall year using GIS. The entire procedure followed for this study is illustrated in the flowchart (Fig. 1.2).

2.6 Identification and Prioritization of Suitable Sites

After identifying RWH potential zones in the basin, suitable sites for constructing RWH structures (farm ponds) and artificial recharge structures (percolation tanks and check dams) were determined by overlaying the thematic layers of the slope, rainfall, soil, LULC, and stream network in the GIS environment. From the pertinent and critical review of past literature (Chowdary et al., 2009; Jha et al., 2014) and professional experience, the suitability criteria for each RWH structure used in this study were finalized and are summarized in Table 1.1. Agricultural lands are suitable for the construction of farm ponds, while percolation tanks (on the ground) in degraded forest and pasture lands. On the other hand, for the check dams and percolation tank (along the stream), a stream-order buffer map was developed by

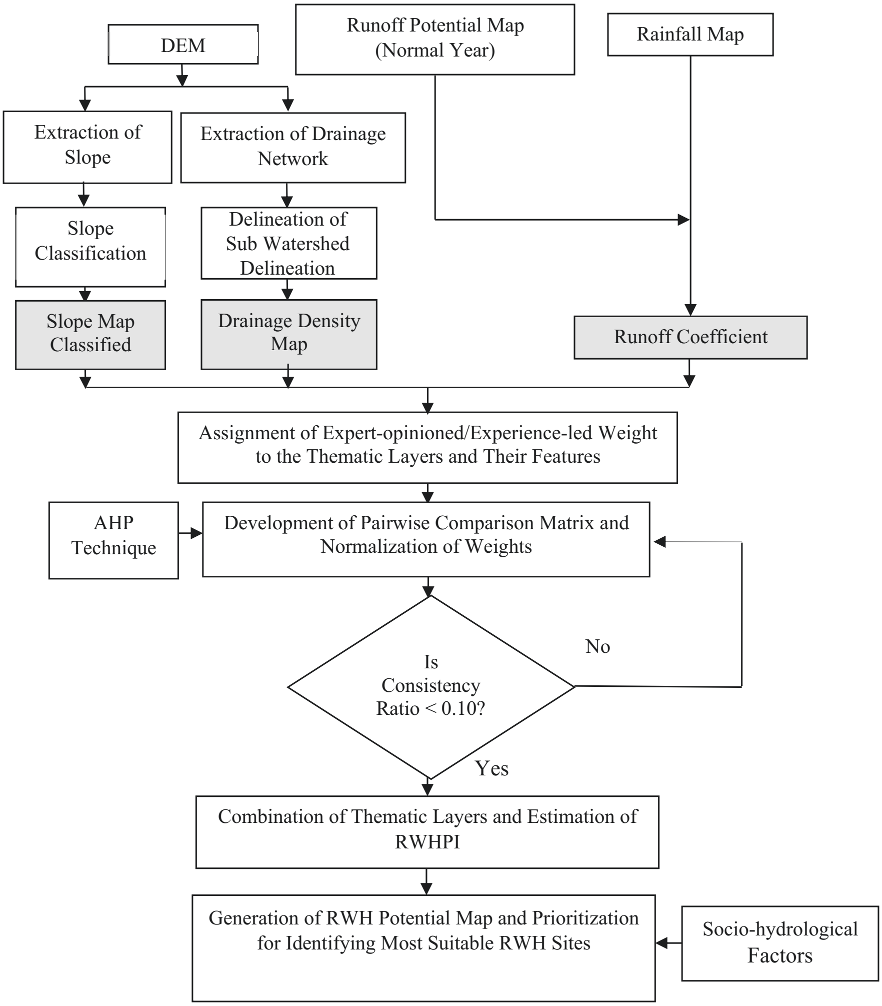


Fig. 1.2 Framework of the methodology adopted in the study

extracting all the 3rd order streams of 100 m buffer from the stream network map. The specified suitability criteria (Table 1.1) were applied to the integrated map using the GIS-based Boolean logic method, and suitable sites were identified for building the RWH and artificial recharge structures.

Additionally, the RWH and artificial recharge sites were prioritized considering socio-hydrologic factors for the cost-beneficial execution of RWH measures. For the prioritization of farm ponds, a settlement buffer of 500 m, an irrigation command area for major and medium dams, and a safe groundwater-level zone during the post-monsoon season were considered. On the other hand, priority sites for

Table 1.1 Suitability criteria used for RWH and artificial recharge structures identification

SI. no.	RWH/recharge structures	Land slope	Soil	Land use/land cover	Drainage order
1	Farm pond	<3%	Fine texture (dense clay at moderate depth)	Agriculture	–
2	Percolation tank (on the ground)	<3%	Loam (very shallow, shallow, and deep depth)	Degraded forest and pasture land	–
3	Percolation tank (along the stream)	<5%	Loam	–	3rd
4	Check dam	<15%	Fine texture (clay at shallow depth and dense clay at moderate depth)	–	3rd

check dams were selected considering minimum spacing of 5 km between two consecutive dams and a 500 m buffer for the proximity of these structures to the settlement. It should be noted that somewhat arbitrary spacing is considered between the two check dams, which can be altered when the RWH plan is implemented after essential field investigations.

3 Results and Discussion

3.1 Features of the Thematic Layers

3.1.1 Land Use/Land Cover

The study area has classified in twelve main land use/cover (LULC) classes, which are (a) agriculture, (b) wasteland, (c) dense forest, (d) fallow land, (e) mining area, (f) open forest, (g) plantation, (h) river/water bodies, (i) rural settlement, (j) degraded forest, (k) pastureland, and (l) urban settlement. The spatial distribution of LULC for the study area is depicted in Fig. 1.3. Most of the LULC is under agriculture (79%), succeeded by pastureland (9%) and fallow land (6%).

3.1.2 Soil

The study area has three types of soil, i.e., loam, clay, and dense clay (Fig. 1.4). Dense clay soil covers the majority of the area, around 45%, followed by clay, 30%, and loamy soil, 25%. The depth of soil is shallow for the clay soil, very shallow to deep for the loam type, and moderately deep to very deep for the dense clay soil, which was respectively classified on the basis of soil physical properties into hydrologic soil groups (HSG) B, C, and D.

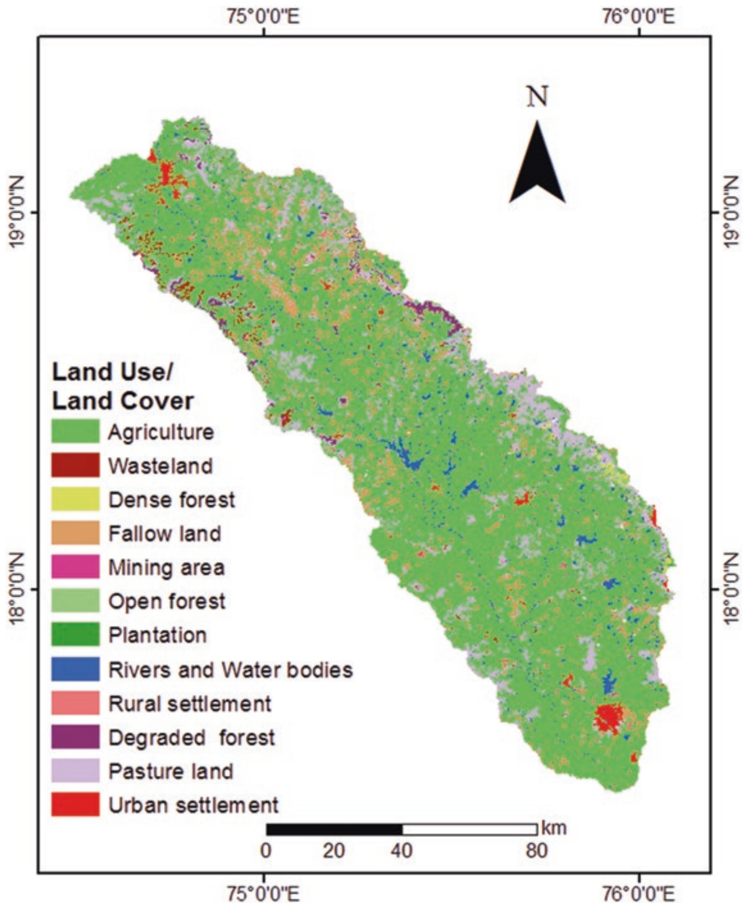


Fig. 1.3 Land use/land cover map of the study area

3.1.3 Slope

The topographic slope map (Fig. 1.5) reveals that the slope varies from zero (level) to 55% (very steep). The study area's land slopes were classified into six dominant classes (Jha et al., 2014): (a) nearly level (0–1%), (b) gentle (1–3%), (c) moderately gentle (3–5%), (d) steep (5–10%), (e) moderately steep (10–15%), and (f) very steep (15–55%). It is clear from Fig. 1.5 that 5820 km^2 (48% of the study area) has a nearly level slope and 4362.61 km^2 (36%) has a gentle slope. These two slope classes are suitable for designing rainwater harvesting (RWH) sites. Several small patches in the river basin are characterized as moderately gentle with a total area of 1236 km^2 (10%), and the zones having steep slopes (including moderately steep and very steep slopes) cover 823 km^2, i.e., only 7% which located in the northeast portion of the study area.

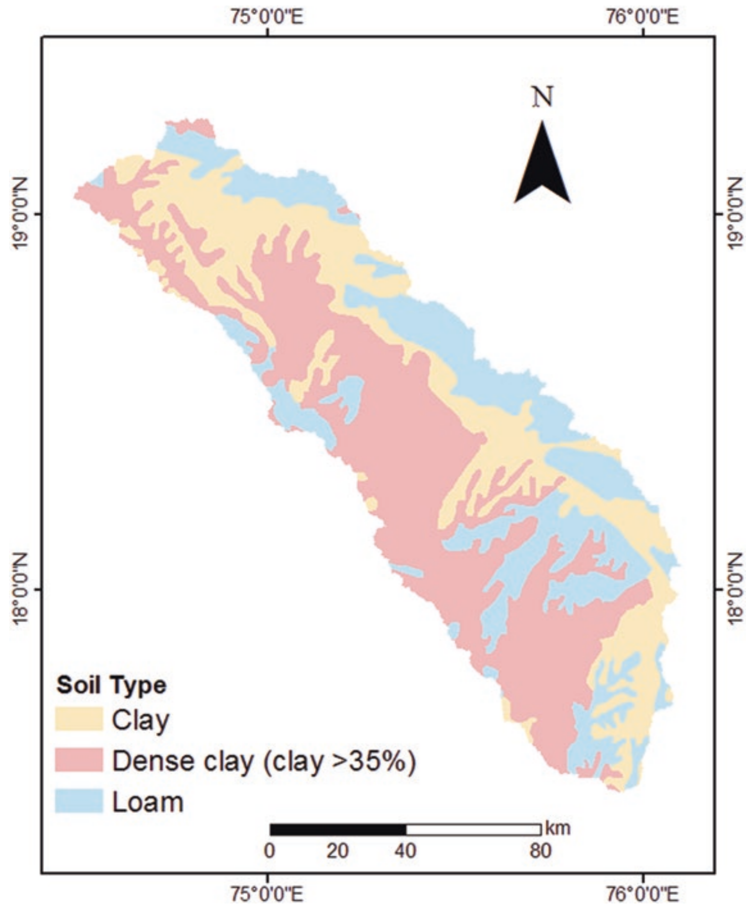


Fig. 1.4 Soil map of the study area

3.1.4 Drainage Network

The prepared drainage network map (Fig. 1.6) reveals that the channel in the river basin area has a maximum order of seven. It is evident from the figure that first-order streams have maximum drainage with a length of 6295 km (53% of the total length). The second-order streams have a drainage length of 2850 km (24%), whereas second-order streams have a drainage length of 1466 km (12%). The fourth- and fifth-order drainage networks have 681 and 357 km lengths, which constitute 6% and 3% of the total drainage lengths, respectively. The remaining part is only 1% of the total length and is covered by both sixth- and seventh order streams with 148 km and 139 km, respectively.

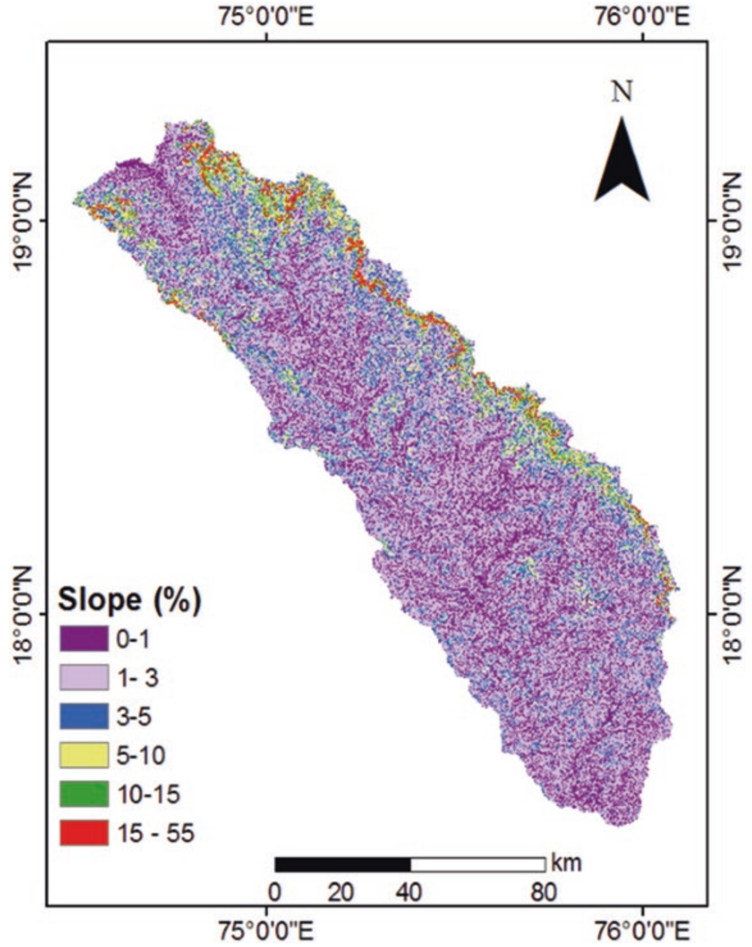


Fig. 1.5 Slope map of the study area

3.1.5 Drainage Density

The spatial drainage density values vary from 0.40 to 1.17 km/km^2 (Fig. 1.7). Based on the values of the drainage density, the sub-watersheds were classified into three categories: (a) low (<0.5 km per km^2), (b) moderate (0.5–1.0 km per km^2), and (c) high (>1.0 km per km^2). A substantial part of the study area falls under the high drainage density class, encircling an area of 8986 km^2 (73%). This class is dominantly occupied, except for the northern part of the study area. The moderate drainage density zone covers an area of 3178 km^2 (26%). On the other hand, only one micro-watershed comes under the low drainage density category having an area of 80 km^2 (1%), located in the northeast part of the study area. It is worth mentioning that the areas with high drainage density values are unsuitable for constructing

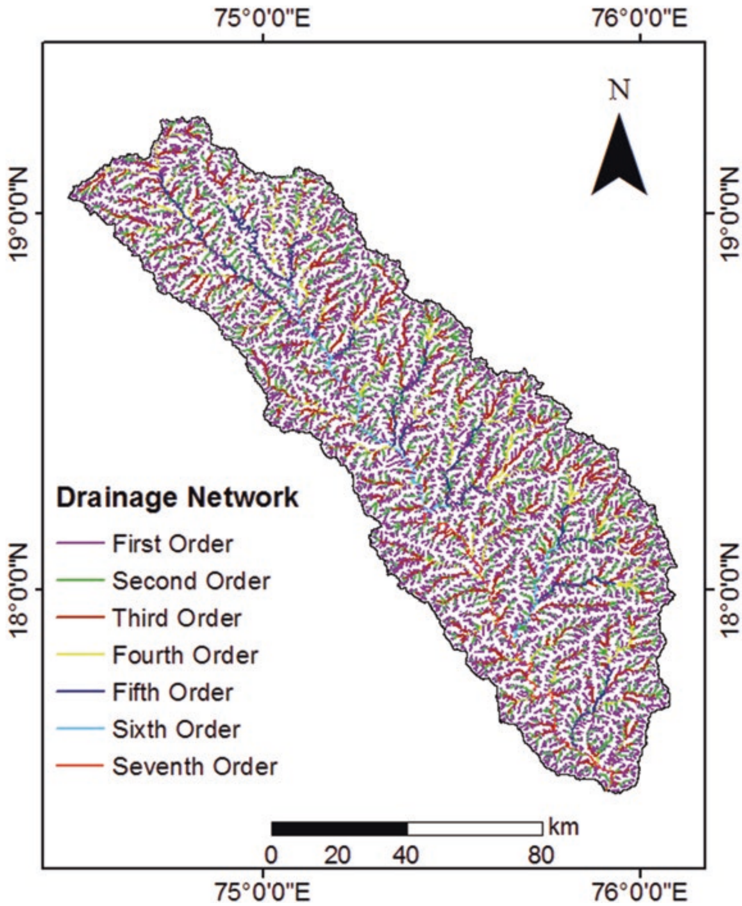


Fig. 1.6 Drainage network map of the study area

RWH structures as the water will drain faster, and therefore there will be less water to store. Hence, these areas were eliminated from the computation, and only the zones having low drainage density were preferred for selecting RWH structures in the construction sites.

3.2 Runoff Coefficient Maps

Runoff coefficient (RC) maps were developed for the wet year (1998), normal year (2000), and dry year (2003), which are presented in Figs. 1.8a–c. The study area is classified into four classes with respect to the spatial variation of RC values: (i) very high (>0.40), (ii) high (0.3–0.4), (iii) moderate (0.2–0.3), (iv) low (0.1–0.2), and (v)

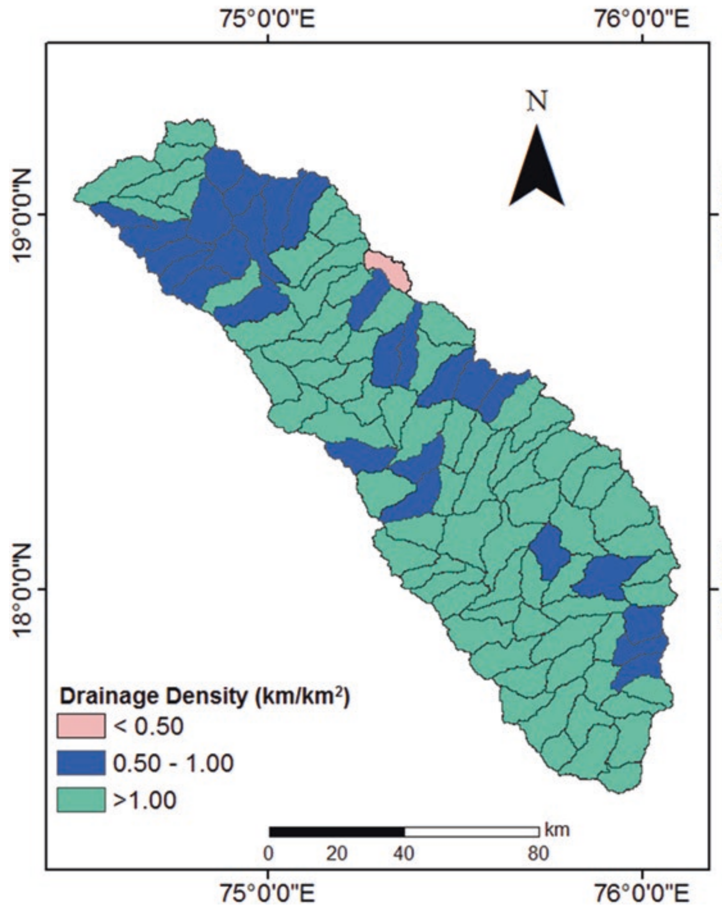


Fig. 1.7 Drainage density map of the study area

very low (<0.1). For the wet year, the RC map of the study area is shown in Fig. 1.8a. It is seen that a major part of the study area has a high RC which covers an area of 7499 km^2 (61%) and is spread in northeast/north and southeast/south parts of the study area. The area has moderate RC and is spread over the lower and northeastern parts, covering about 3303 km^2 (27%). The areas under very low, low, and very high RC categories are 249 km^2 (2%), 499 km^2 (4%), and 693 km^2 (6%), respectively. The RC map for the normal year (Fig. 1.8b) reveals that most of the study area is covered by low and moderate RC categories, covering an area of 5935 km^2 (48%) and 5146 km^2 (42%), respectively. The zones falling under moderate RC class are in the northeast/north and southeast/south portions of the study area, whereas low RC class falls in the northeast and southeast/south parts. The very low RC class covering an area of 749 km^2 (6%) is observed in a narrow strip in the northeast part of the study. The very high RC class incorporating an area of 414 km^2 (3%) is seen

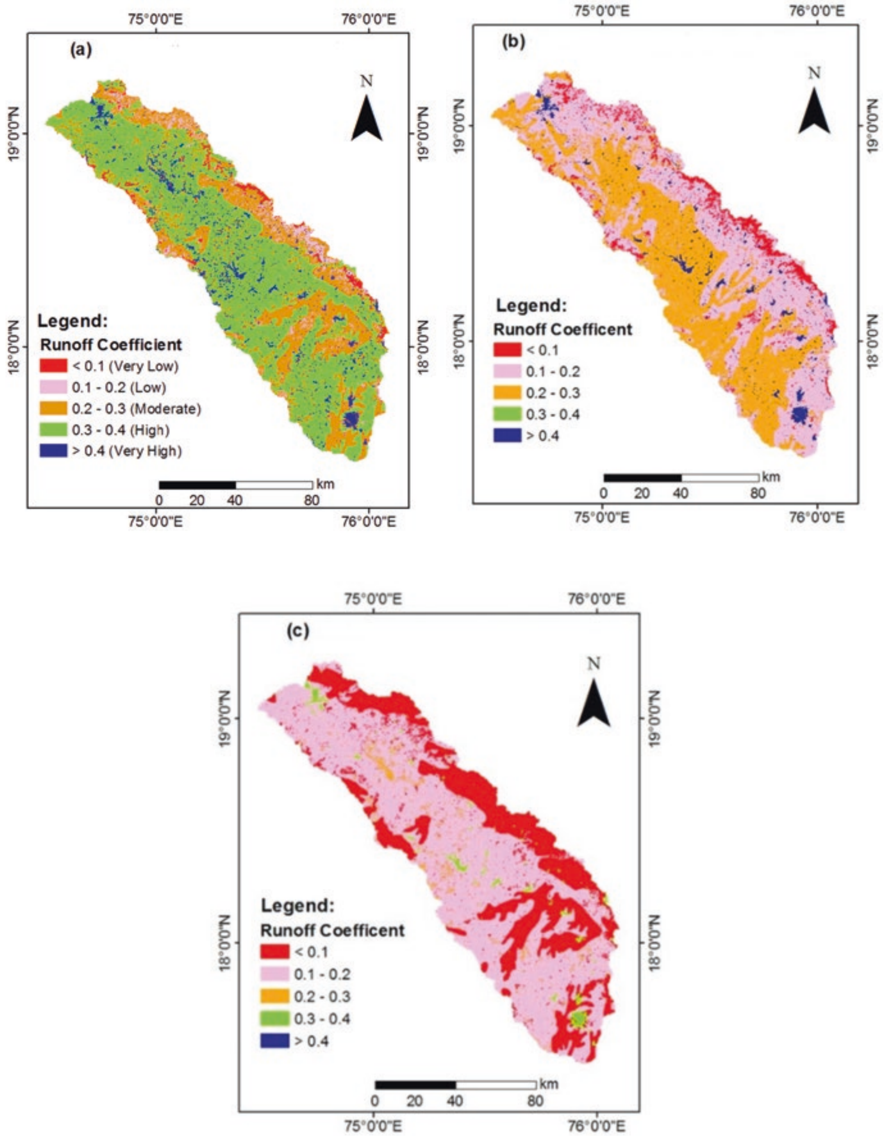


Fig. 1.8 Runoff coefficient map of the study area for (**a**) wet year (1998), (**b**) normal year (2000), and (**c**) dry year (2003)

in small patches over the area. The RC map of the study area for the dry year (Fig. 1.8c) shows that the low runoff coefficient class zone covers a major part of the study area (7890 km^2; 64%) on the northeast/north and southeast/south side. Also, the very low RC class encompasses 3661 km^2 (30%) area and is spread in the north-east and lower parts.

Table 1.2 Pairwise comparison matrix and normalized weights of the thematic layers

Thematic layer	Assigned weight	Thematic layer			Normalized weight
		Runoff coefficient	Slope	Drainage density	
Runoff coefficient	9	9/9	9/8	9/6	0.391
Slope	8	8/9	8/8	8/6	0.348
Drainage density	6	6/9	6/8	6/6	0.261
Total					1

Table 1.3 Weights assigned and the normalized weights of the thematic layers and their corresponding features

Thematic layer	Feature class	Weight assigned	Normalized weight
Runoff coefficient	Very high: >0.4	8	0.333
	High: 0.3–0.4	6	0.250
	Moderate: 0.2–0.3	5	0.208
	Low: 0.1–0.2	3	0.125
	Very low: <0.1	2	0.083
Slope	Nearly level: 0–1%	9	0.346
	Gentle: 1–3%	7	0.269
	Moderately gentle: 3–5%	5	0.192
	Steep: 5–10%	3	0.115
	Moderately steep: 10–15%	1	0.038
	Very steep: 15–55%	1	0.038
Drainage density	Low: <0.5	8	0.471
	Moderate: 0.5–1	6	0.353
	High: >1	3	0.176

3.3 *Assignment of Weights to Thematic Layers*

The weights allotted to the thematic layers were normalized by applying AHP and Eigenvector techniques. These are compiled in Table 1.2, along with the respective pairwise comparison matrix. The allotted weights associated with the respective thematic layers were found consistent as the consistency ratio is not more than 0.10 for all three thematic layers. Similarly, appropriate weights allocated to the features of each thematic layer were normalized (Table 1.3). In this case, the consistency ratios were also not more than 0.10 for all the features of the thematic layers, which indicates the consistency of the assigned weights.

3.4 *Rainwater Harvesting Potential Map*

The RWH potential map of the study area was developed (Fig. 1.9) by combining the concerned thematic layers and then calculating the rainwater harvesting potential index (RWHPI) in the GIS environment. On the basis of obtained RWHPI

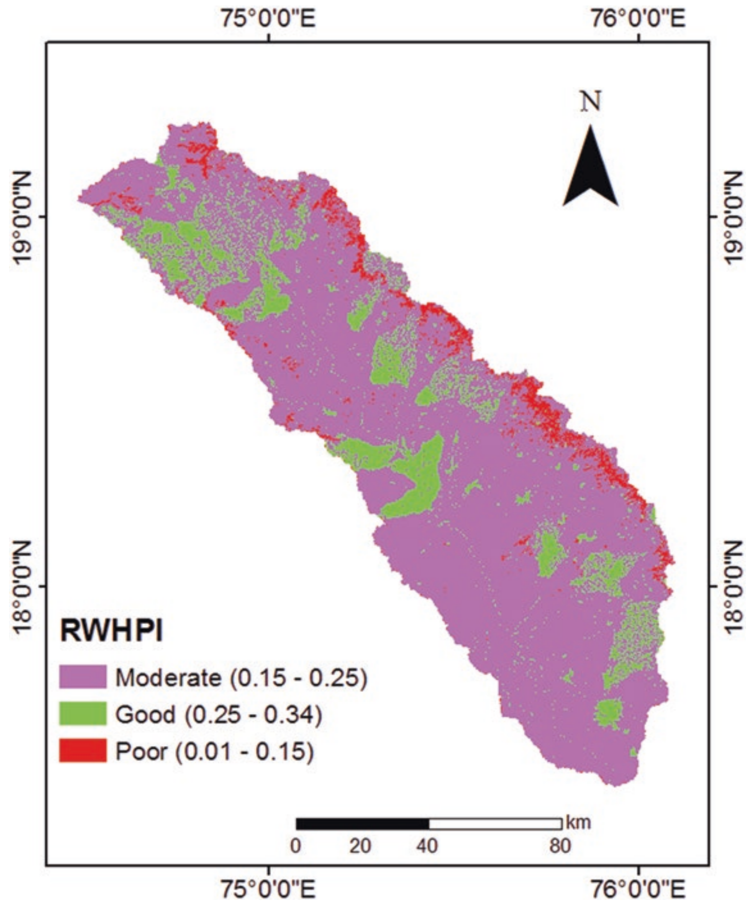


Fig. 1.9 Map showing RWH potential zone classes in the study area

values (0.01–0.34), the study area was classified into three zones indicating: (a) good (RWHPI = 0.25–0.34), (b) moderate (RWHPI = 0.15–0.25), and (c) poor (RWHPI = 0.01–0.15) RWH potential. The area having good RWH potential is 1930 km^2 (16%), which extends into the small patches in the study area. The moderate RWH potential zone is large in the study area covering 80% of the study area (9802 km^2). The area with poor RWH potential is about 513 km^2 (about 4%), extending in small strips in the eastern and northeastern parts. The main reason for this poor RWH potential zone is that moderately steep to very steep slope (10–55%) prevails in this zone. Based on the developed RWH potential map, suitable areas were identified for RWH measures to conserve rainwater and augment groundwater in the area.

3.5 Zones/Sites for RWH and Artificial Recharge Structure

For the construction of different RWH structures, suitable RWH sites are chosen based on land slope, LULC cover, drainage order, and soil type (Table 1.1). Agricultural land is most appropriate for excavating farm ponds (Table 1.1) as harvested water can be used for supplemental irrigation. Two types of fine textural soil are available in the study area, (i) dense clay and (ii) clay soil. The dense clay soil is available at moderate to very deep depths. Hence, considering the depth of farm ponds, the area having dense clay is considered for farm pond excavation. However, the depth of clay soil is shallow (25–50 cm); the zones having clay soil are not suitable for farm ponds. The zone appropriate for farm pond is 35% (4236 km^2), spread over southeast/south portions of the study area (Fig. 1.10). In contrast, suitable areas for percolation tanks (on the ground and along the stream) are only 1% each, which

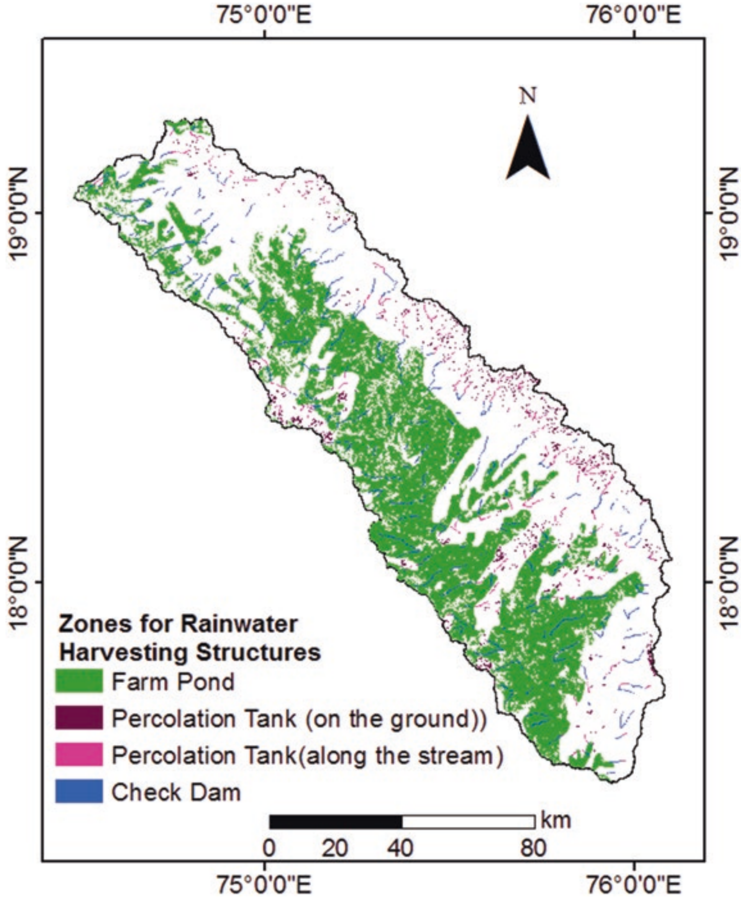


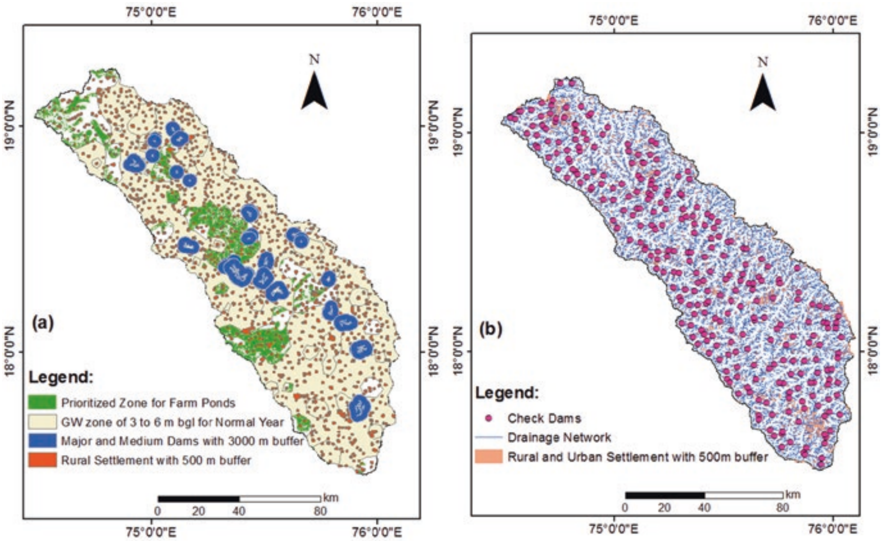
Fig. 1.10 Map of suitable zones for rainwater harvesting structures in the study area

cover scattered mostly northeastern parts of the study area. For the construction of check dams, an area of 270 km^2 (2% of the study area) is found applicable.

3.6 Prioritized Sites/Zones for RWH and Artificial Recharge

Based on the GIS analysis, 46,952 locations are found to be appropriate for farm ponds, which are practically infeasible. Hence, the sites for farm ponds are prioritized based on the proximity of rural settlements, irrigation commands under major/medium dams, and safe groundwater levels. However, the command area maps of each major and minor dam are not available, but the area of irrigation command is known. Hence, the buffer of 3000 m is estimated based on the average area of irrigation command (30 km^2) under major/medium projects. Further, this buffer is applied for the entire major/medium irrigation projects because farm pond construction within this buffer is unnecessary. In addition, the farm pond zone beyond the area having 3–6 m depth to post-monsoon water table during normal years is preferred since it is assumed that this zone of groundwater would be available for irrigation. Hence, out of the total area under farm pond, the area outside of rural settlement has a buffer of 500 and 3000 m buffer of major and minor irrigation projects, and the buffer of 3–6 m depth to post-monsoon water table is used to prioritize farm ponds as shown in Fig. 1.11a. The area of the prioritized zone of the farm pond is 1098 km^2, which is 11% area of the agriculture area (9616 km^2).

Furthermore, considering suitability criteria (Table 1.1), 8546 sites are found suitable for check dams, which are practically infeasible. For this prioritization of



Figs. 1.11 Prioritized sites for RWH structures (**a**) farm pond and (**b**) check dam

check dams, based on the regional/local experience, the minimum distance between two conservative check dams is considered 5 km, and the proximity of this structure to the settlement is taken as a 500 m buffer. In this way, in the study area, 284 sites are prioritized for check dams, as shown in Fig. 1.11b. During field implementation of the proposed plan, the prioritized check dam sites can be further optimized depending upon the streamflow availability, amount of water harvested per structure, and local conditions. The prioritized sites for farm ponds and check dams can be used for the cost-effective implementation of the RWH plan.

4 Conclusions

In any area/region, rainwater harvesting (RWH) plays the main role in mitigating the impacts of droughts. The present study illustrates the capability of geospatial techniques and multi-criteria decision analysis (MCDA) methods for planning RWH measures in the study area. Further, appropriate sites/zones for RWH and artificial groundwater recharge have been identified for efficient water management. Prioritization of these sites/zones has also been carried out for the cost-effective implementation of water conservation strategies considering some socio-hydrological criteria. The major findings drawn from the analysis of the results are as follows:

- The runoff coefficient for most of the study area varies from moderate (0.2–0.3) to high (0.3–0.4) in the wet year, low (0.1–0.2) to moderate in the dry year, and very low (0.0–0.1) to low in the dry year. Approximately 14% of the total rainfall received over the basin is transformed into the runoff.
- The rainwater harvesting potential of the area varies from 0.01 to 0.34 in normal years. About 80% of the study area (9802 km^2) comes under the moderate RWH potential (0.15–0.25) zone, while about 16% (1930 km^2) of the total basin has good (0.25–0.34) RWH potential.
- A total of 8546 sites are found suitable for check dams covering an area of 270 km^2 (2% of the area), while 46,952 locations are found to be appropriate for farm ponds covering (4236 km^2) 35% of the study area. Suitable lands for percolation tanks (both “on the ground” and “along the stream”) cover an area of 260 km^2 (2% of the study area).
- For the economical implementation of RWH structures in the study area, 11% of the agricultural land is prioritized for the excavation of farm ponds, and 284 sites and construction of check dams in the study area are prioritized.

Overall, this study demonstrates the use of the GIS-MCDA integrated tool for assessing the RWH potential zones, identifying the most suitable locations for the RWH, and augmenting the groundwater from a socio-hydrologic aspect for cost-effective implementation. On the overlapping cadastral map on the RWH maps, this study can help water managers with effective planning for RWH and artificial groundwater recharge structures to combat the droughts in the study area, particularly in the rainfed farming areas. The field survey for the validation of the suggested sites for RWH structures is recommended as a follow-up to this study.

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References

Al-Ghobari, H., Dewidar, A., & Alataway, A. (2020). Estimation of surface water runoff for a semi-arid area using RS and GIS-based SCS-CN method. *Water, 12*(7), 1924. https://doi.org/10.3390/w12071924

All India Report on Agriculture Census 2010–11. (2015). *Agriculture Census Division Department of Agriculture*. Cooperation & Farmers Welfare Ministry of Agriculture & Farmers Welfare, Government of India.

Bamne, Y., Patil, K. A., & Vikhe, S. D. (2014). Selection of appropriate sites for structures of water harvesting in a watershed using remote sensing and geographical information system. *International Journal of Emerging Technology and Advanced Engineering, 4*(11), 270–275.

Chowdary, V. M., Ramakrishnan, D., Srivastava, Y. K., Chandran, V. & Jeyaram, A. (2009). Integrated water resource development plan for sustainable management of Mayurakshi watershed, India using remote sensing and GIS. *Water resources management, 23*(8): 1581–1602.

Chowdhury, A., Jha, M. K., & Chowdary, V. M. (2010). Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal using RS, GIS and MCDM techniques. *Environmental Earth Science, 58*(6), 1209–1222.

CWC. (2005). *Hand book of water resources statistics, Central Water Commission (CWC)*. Ministry of Water Resources, Government of India.

DTE. (2015). *India must focus on rainfed farming*. Down to Earth (DTE). https://www.downtoearth.org.in/coverage/india-must-focus-on-rainfed-farming6259#:~:text=It%20accounts%20for%2068%20per,86%20million%20ha%20is%20 rainfed. Accessed on 10 July 2020.

FAO. (2003). *Training Course on Water Harvesting* (Land and water digital media series: CD-ROM No. 26). Food and Agriculture Organization of the United Nations (FAO).

FAO. (2012). *Coping with water scarcity: An action framework for agriculture and food security*. Food and Agriculture Organization of the United Nations.

Ghayoumian, J., Saravi, M. M., Feiznia, S., Nouri, B., & Malekian, A. (2007). Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. *Journal of Asian Earth Sciences, 30*(2), 364–374.

Jarvis, A., Guevara, E., Reuter, H. I., & Nelson, A. D. (2008). *Hole-filled SRTM for the globe: Version 4: Data grid*. Web publication/site, CGIAR Consortium for Spatial Information. http://srtm.csi.cgiar.org/

Jasrotia, A. S., Majhi, A., & Singh, S. (2009). Water balance approach for rainwater harvesting using remote sensing and GIS techniques, Jammu Himalaya, India. *Water Resources Management, 23*(14), 3035–3055.

Jha, M. K., Chowdary, V. M., Kulkarni, Y., & Mal, B. C. (2014). Rainwater harvesting planning using geospatial techniques and multicriteria decision analysis. *Resources, Conservation and Recycling, 83*, 96–111.

Kadam, A. K., Kale, S. S., Pande, N. N., Pawar, N. J., & Sankhua, R. N. (2012). Identifying potential rainwater harvesting sites of a semi-arid, basaltic region of western India, using SCS-CN method. *Water Resources Management, 26*(9), 2537–2554.

Kahinda, J. M., & Taigbenu, A. E. (2011). Rainwater harvesting in South Africa: Challenges and opportunities. *Physics and Chemistry of the Earth, Parts A/B/C, 36*(14-15), 968–976.

Mahmoud, S. H., Adamowski, J., Alazba, A. A., & El-Gindy, A. M. (2016). Rainwater harvesting for the management of agricultural droughts in arid and semi-arid regions. *Paddy and Water Environment, 14*(1), 231–246.

Malczewski, J. (1999). *GIS and multicriteria decision analysis*. Wiley.

MoWR, & CGWB. (2013). *Ground Water Information Solapur District Maharashtra*. Ministry of Water Resources/Central Ground Water Board (CGWB), Central Region.

Oweis, T., Oberle, A., & Prinz, D. (1998). Determination of potential sites and methods for water harvesting in central Syria. *Advances in Geoecology, 31*, 83–88.

Parthasarathy Committee Report. (2006). *From Hariyali to Neeranchal: Report of the technical committee on watershed programmes in India*. Department of Land Resources, Ministry of Rural Development, Government of India.

Ramakrishnan, D., Durga Rao, K. H. V., & Tiwari, K. C. (2008). Delineation of potential sites for water harvesting structures through remote sensing and GIS techniques: A case study of Kali watershed, Gujarat, India. *Geocarto International, 23*(2), 95–108.

Rockstrom, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., & Qiang, Z. (2010). Managing water in rainfed agriculture—The need for a paradigm shift. *Agricultural Water Management, 97*, 543–550.

Saaty, T. L. (1980). *The analytic hierarchy process*. McGraw-Hill.

Sahoo, P. K. (2004). *Selection of sites for water harvesting structures using GIS*. Unpublished M.Tech Thesis, Agricultural and Food Engineering Department, IIT Kharagpur, West Bengal, India.

SCS. (1985). *National engineering handbook, Section 4, hydrology. Soil Conservation Service (SCS)*. US Department of Agriculture (USDA).

Singh, V. P. (1992). *Elementary hydrology* (pp. 474–482). Prentice-Hall of India Private Limited.

Singh, L. K., Jha, M. K., & Chowdary, V. M. (2017). Multi-criteria analysis and GIS modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply. *Journal of Cleaner Production, 142*, 1436–1456.

Subramanya, K. (2008). *Engineering hydrology* (pp. 155–160). Tata McGraw-Hill Publishing Company Limited.

Toosi, A. S., Tousi, E. G., Ghassemi, S. A., Cheshomi, A., & Alaghmand, S. (2020). A multi-criteria decision analysis approach towards efficient rainwater harvesting. *Journal of Hydrology, 582*, 124501.

Voogd, H. (1983). *Multicriteria evaluation for Urban and Regional Planning*. Pion Limited, 361 pp.

Wable, P. S., Jha, M. K., & Shekhar, A. (2018). Comparison of drought indices in a semi-Arid River Basin of India. *Water Resources Management, 33*(1), 75–102.

Wani, S. P., Venkateswarlu, B., & Sharda, V. N. (2011). Watershed development for rainfed areas: Concept, principles, and approaches. In Wani et al. (Eds.), *Integrated watershed management in rainfed agriculture* (pp. 53–86). CRC Press/Taylor and Francis Group.

Weerasinghe, H., Schneider, U. A., & Loew, A. (2011). Water harvest-and storage-location assessment model using GIS and remote sensing. *Hydrology and Earth System Sciences Discussions, 8*(2), 3353–3381.

Ziadat, F., Bruggeman, A., Oweis, T., Haddad, N., Mazahreh, S., Sartawi, W., & Syuof, M. (2012). A participatory GIS approach for assessing land suitability for rainwater harvesting in an arid rangeland environment. *Arid Land Research and Management, 26*(4), 297–311.