



Research Article

Assessment of recharge potential zones for groundwater development and management using geospatial and MCDA technologies in semiarid region of Western India



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Received: 21 September 2019 / Accepted: 21 January 2020 / Published online: 31 January 2020
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Abstract

Groundwater recharge potential (GWRP) plays a vital role as it directly or indirectly supports domestic, agriculture and industrial activities by infiltrating the rainwater. The present paper touches upon the methodology delineating groundwater recharge potential zones by applying geospatial and multi-criteria decision analysis (MCDA) to the derived thematic layers based on significant influence of occurrence of groundwater in semiarid watershed of Western India. The satellite imageries and other ancillary data were utilized to generate various thematic layers, viz. slope, geology, drainage density, surface run off, geomorphology, land use/land cover soil and vadose zone. The outcome of study shows that about 24.69% is having high GWRP and 24.17% of the area is moderate for recharge of groundwater, while the low and poor groundwater recharges potential area is about 44.34% and 6.80% of total area, respectively. The validation of the study was done by overlaying point data groundwater well yield on the output final map; it shows good correlation with result. Also, the surplus water availability was calculated based on vadose calculation according to CGWB method; it shows 17.12 MCM vadose region having artificial recharge of 22.77 MCM. The total recharge is about 117.41 MCM, about 30% of the total runoff, i.e. 35.22 MCM is considered as surplus monsoon runoff available for artificial recharge. The result shows that the use of remote sensing, geospatial and MCDA technologies are promising and efficiently recognize the suitable regions for groundwater recharge over other conventional techniques.

Keywords Groundwater recharge potential · MCDA · Semiarid watershed · Western India

1 Introduction

Groundwater source is generally safe and prime source of drinking water due to less pollution as compared to the surface water [1–3]. The increasing inhabitants, farming activities and rapid industrialization have led to continuous extraction, depletion and degradation of groundwater. Currently, 85% of rural population in India fulfils the drinking and domestic water demands from groundwater [4, 5]. The recharge of groundwater occurs when rainfall or snowmelt water infiltrates into the aquifer [6,

7]. The occurrence and movement of groundwater are determined by physical edifices, topographic condition, lithological difference, gradient, soil, drainage form and climate [8–10]. Hence, it is necessary to consider all these factors, to understand groundwater recharge potential of an area. The efficient groundwater recharge quantification requires accurate scientific measures and modern techniques [11, 12]. The traditional in situ investigations of groundwater recharge potential are time-consuming and expensive [13–15]. In recent years, with the improvement of modern spatial techniques for hydrological applications,

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the mapping of groundwater recharge potential zones is faster and more cost-effective [16]. Many researchers across the world have carried out groundwater potentiality studies using integrated remote sensing and GIS technique [17–22]. An accurate groundwater recharge potential zones mapping in representative semiarid basin can help in resourceful management of this vital source and decrease the groundwater susceptibility in the region [12, 23]. Therefore, an effort has been made in this study to define groundwater recharge potential zones of Shivganga watershed using MCDA, in preparation of groundwater development plan.

2 Study area

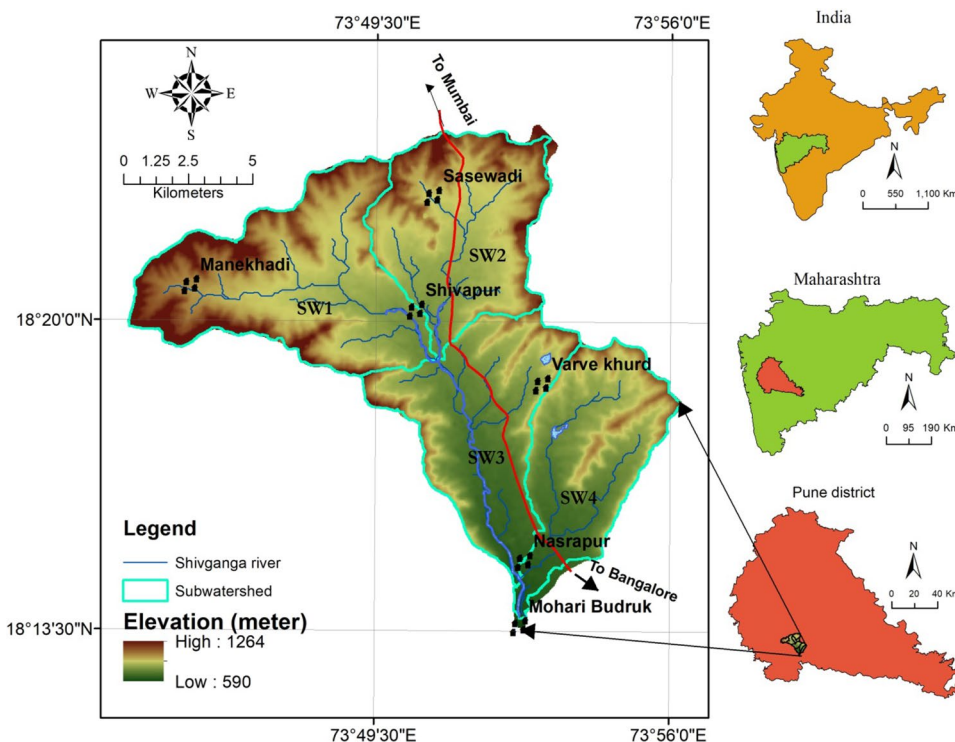
The Shivganga watershed is situated at lower altitude of Western Ghats and has an aerial extent of about 177 km². The study area lies between longitudes 73°44'1.131" E and 73°56'17.941" E and latitude 18°13'36.059" N to 18°24'7.466" N (Fig. 1). It is represented in the Survey of India (SOI) topographic sheet numbers 47F/15 and 47F/16 on 1:50,000 scale. The study area is categorized into four sub-watersheds based on the drainage divided. The area receives average rainwater of 964 mm from south-westerly monsoon between June and September. The climate of the area is semiarid having average temperature 36 °C during summer and about 18 °C during winter. Shivganga River originates at Sinhagad fort foothills and further

confluence with Gunjawani River near Mohari Budruk vil-lage. The high elevation patch is situated in western part (1264 m) and lower elevation (590 m) is in easternmost portion of region [24, 25].

3 Methodology

The GWR potential has been assessed for quantification of groundwater recharge in study area. Figure 2 portrays the technique of implemented and procedures adopted for groundwater recharge potential mapping in the study area. The study area base map, watershed and sub-watershed maps were demarcated from topographic map and natural drain lines. Strahler (1957) stream ordering scheme was used for giving orders to natural drain lines. Study area was divided into four sub-watersheds: SW1, SW2, SW3 and SW4 (Fig. 1), which future used for calculation of recharge potential area. The drainage density (Dd) map was derived from the natural drain lines in ArcGIS platform. The contour map combined with ASTER data was used to generate the elevation map, which further used for deriving slope and validated with field triangulation points for better accuracy. The resource maps with ground-based data were used for preparation of geomorphology, geology and soil maps of the study area. The geomorphology map was procured from the National Atlas and Thematic Mapping Organisation (NATMO), which is further updated using satellite image. The geology map was purchased

Fig. 1 Location map of Shivganga basin



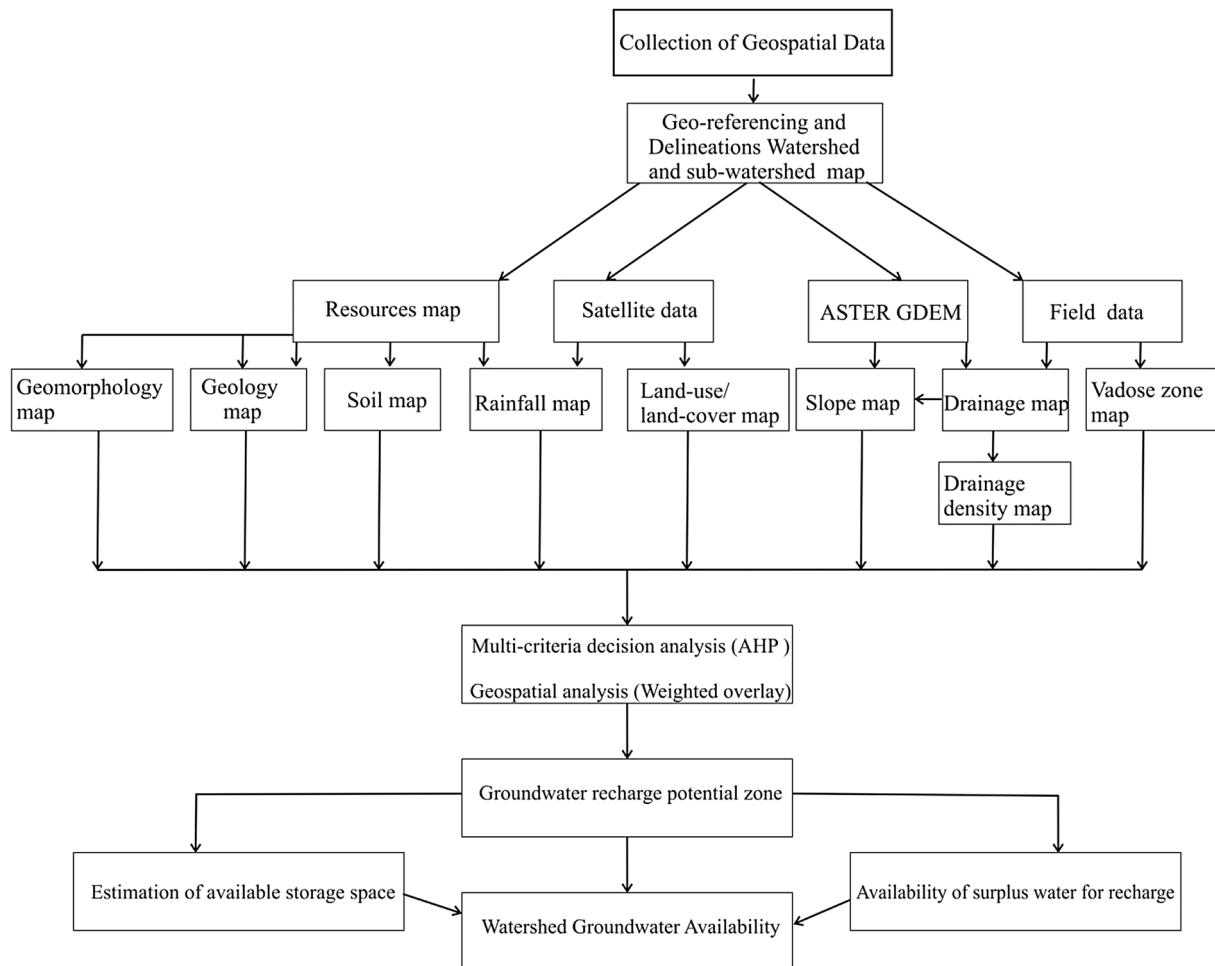


Fig. 2 Flowchart for delineating the groundwater recharge potential zone

from the Geological Survey of India (GSI), which is further updated using satellite image. Soil map was purchased from National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) Nagpur. The land use/land cover map was prepared from LANDSAT image and updated with corrected with satellite imageries available on Google and Bhuvan websites. The rainfall map was prepared by Thiessen polygon method in GIS environment and updated with remote sensing-based Tropical Rainfall Measuring Mission (TRMM) monthly rainfall data from NASA for preparation spatial variation in rainfall of study area. The vadose zone map was prepared by the change in groundwater level data of pre- and post-monsoon data. UTM projection and WGS-84 co-ordinate system were assigned to all thematic layers with 30 m pixel resolution and converted to raster format for performing weighted overlay analysis using GIS software. Multi-criteria decision analysis (MCDA) method such as AHP is used to delimit the weightage of feature layer to eliminate the biasness in the output map. Based on MCDA analysis, resultant weightage was given to the

thematic layer and suitable ranking was allotted to each class of respective theme [24, 25]. The rank was assigned in the scale of 1–5, where 5 represents the good recharge potential, while the 1 represents poor recharge potential. The recharge potential was classified into poor, low, moderate and high classes.

Based on above identified and groundwater available recharge zone identified using CGWB-based groundwater vadose zone method, the watershed available recharge is calculated as sub-watershed basis. Based on that, the availability surplus water for recharge was calculated, which helps in calculating watershed groundwater availability.

4 Result and discussion

4.1 Geomorphology

Geomorphological investigations throw light on topography, landforms and drainage network. Various processes

such as weathering, erosion and deposition have produced different landform in upstream and downstream sections in the area. The various geomorphic units of the basin have been divided into weathered shallow or weathered terrain, moderately dissected or slightly dissected terrain, mesa/buttes, highly dissected terrain and escarpment (Fig. 3). Among all these, the weathered shallow or weathered terrain that is best for recharge is given the rank 5, while moderately dissected or slightly dissected terrain that is good for groundwater recharge is assigned the value 4. The highly dissected area generates high surface runoff due to exposure of basaltic rock; poor soil cover, steep slopes and scarce vegetation hence possess poor groundwater recharge potential is assign the rank 1.

4.2 Drainage density

The Dd is the fraction of stream length per kilometre square of the area [26]. It indicates the ability of area to recharge the precipitation. It is the function of geology, geomorphology, rainfall, gradient, land utilization pattern and infiltration capacity of vadose zone [27, 28]. Soil and bedrock physiognomies disturb the overland flow in the study area. Drainage density enables a calculable investigation of the typical distance of rivulet conduits elongating the complete part of the watershed area. The resultant map shows the low density area present near main stream at central part of basin increasing towards

peripheral part of basin. The drainage density is classified into excellent to 'very good' (0–0.467 km/km²), 'very good to good' (0.467–1.236 km/km²), 'good to moderate' (1.236–1.841 km/km²), 'moderate to poor' (1.841–2.46 km/km²) and 'poor to very poor' (> 2.46 km/km²) as shown in Fig. 4. Higher density category has been considered as low to poor recharge potential area, showing very less scope for permeability of bedrock, which is assigned the value 1, whereas the lower density area that offers the higher possibility of groundwater recharge is given the value 5.

4.3 Slope

Slope affects the rainwater to infiltrate and overflow and therefore acts as an important parameter for groundwater recharge potential studies [29]. The high slope area results into quick runoff and low retaining period to infiltrate water and thus considered as 'poor' for groundwater recharge, while table land having high water for longer retention time, thus, shows high porosity and permeability rate. The slope map is generated from digital elevation model and reclassified in five slope classes. Figure 5 shows that slope alters from 0 to 25%. The high gradient area established in the periphery of the study area, showing less percolation, which is assigned the value 1, while flat terrain having 0–5% slope occupies majority of the area. This major part of the area was observed in flat terrain

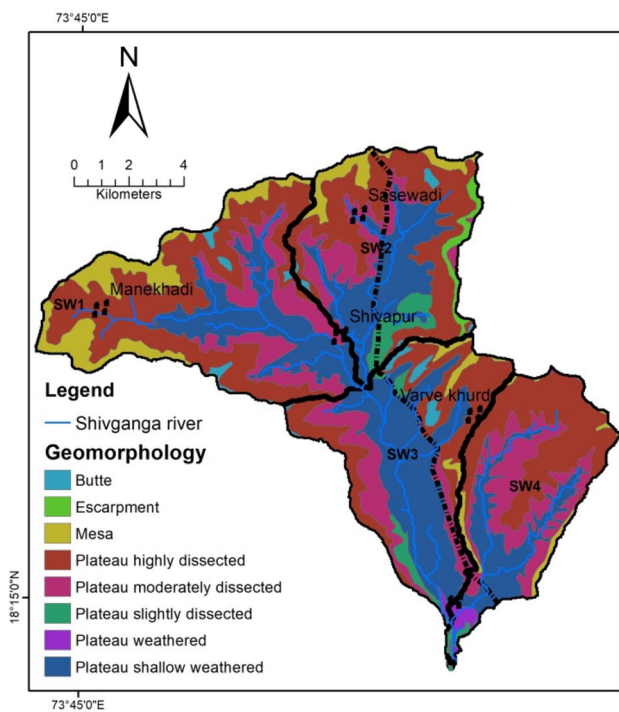


Fig. 3 Geomorphology map

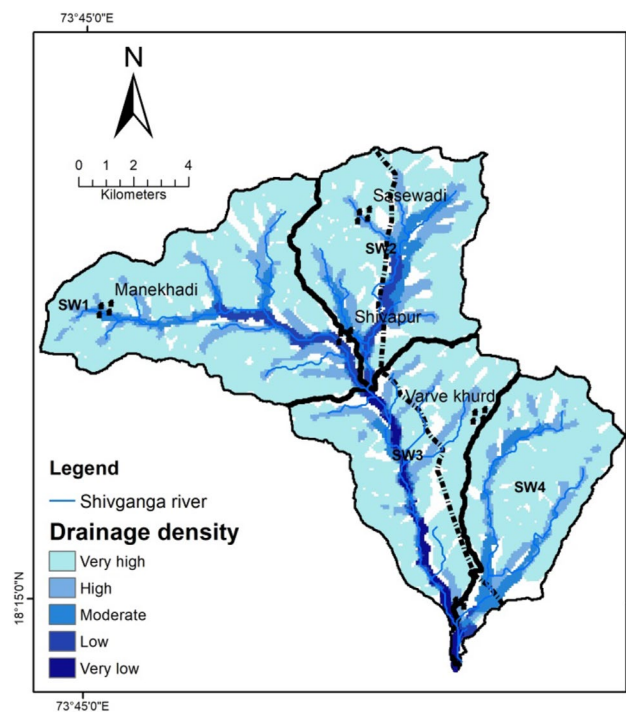


Fig. 4 Drainage density map

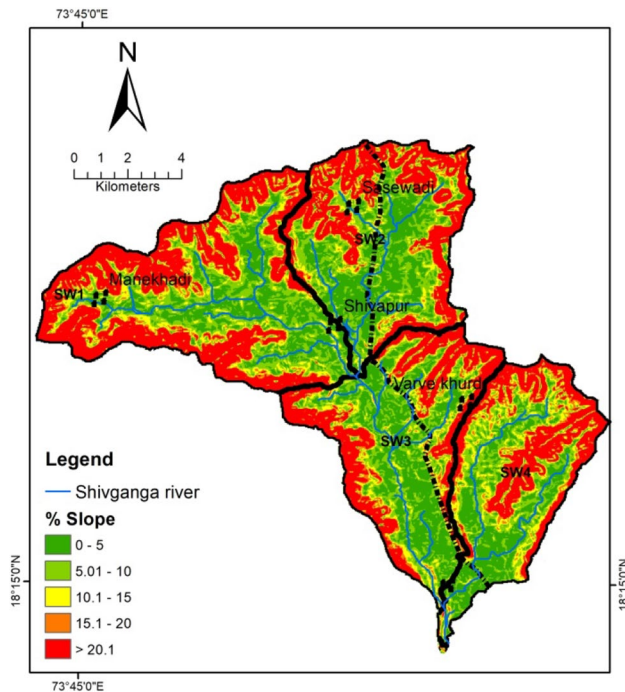


Fig. 5 Slope variation map of study area

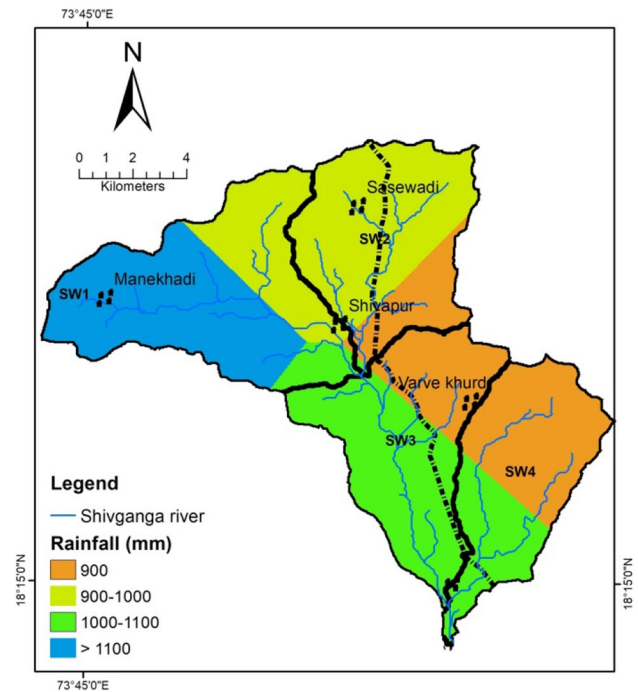


Fig. 6 Rainfall variation map of study area

covering almost 40% of the region; hence, the region is 'good' for groundwater recharge which is assigned the value 5.

4.4 Rainfall

Rainfall is directly related to groundwater recharge potential and determines the availability of water to percolate into the subsurface. The rainfall occurs in the months from June to September. The area also experiences showers from the retreating monsoon in the months of October and November. The average annual rainfall is around 1016 mm recorded from 1950 to 2010. The spatial distribution of rainfall is obtained from TRMM data which reveals that the rainfall increases towards the northwest part of the study area (Fig. 6). Then, the TRMM precipitation grid-based data were added around by 'grid adds' and 'grid mean' tool of GIS to prepared annual average rainfall map. The rainfall area with values less than 900 mm will be assigned the rank 1, while the north-western part having rainfall more than 1100 mm is given the rank 5.

4.5 Geology

The Deccan Volcanic Province having flows belonging to Sahyadri Group particularly Purandargarh and Diveghat formation occupies the study area. This mappable flow is a sub-unit made up of uninterrupted eruption of lava and

the product of single lava. Flow fields are identified on the basis of field relation and morphology. These are generally the eruptions that cover a huge area and contain several lava flow units. The basalt lava flows visible in the region found equally compound pahoehoe and a'a flow forms. There are certain flows showing mixed typescripts. These are of the intermediate nature and display change from pahoehoe to a'a flows. The flows are roughly 400 m thick that includes simple type basalt flows with a few compound flows. The top of Purandargarh formation is marked by 20–25-m-thick megacrystic flow covering bulky plagioclase phenocrysts. Diveghat formation vitrines compound pahoehoe flow with main vesicles covers huge part of the basin area (Fig. 7).

4.6 Soil

Soil plays a supportive vital role in the recharge of groundwater in that area [3, 30]. As per the soil survey map and field study, area is characterized as sandy loam, loam clay and clay types (Fig. 8) [25]. Most of the study regions mainly have HSG-B soil type (48%) and HSG-C soil type (43%). HSG-B soil has good amount of rainwater infiltration due to high perviousness and penetrability; hence, it has been assigned highest priority is given the rank 5. HSG-D soil is compacted and impermeable; hence, given low priority ranks 1.

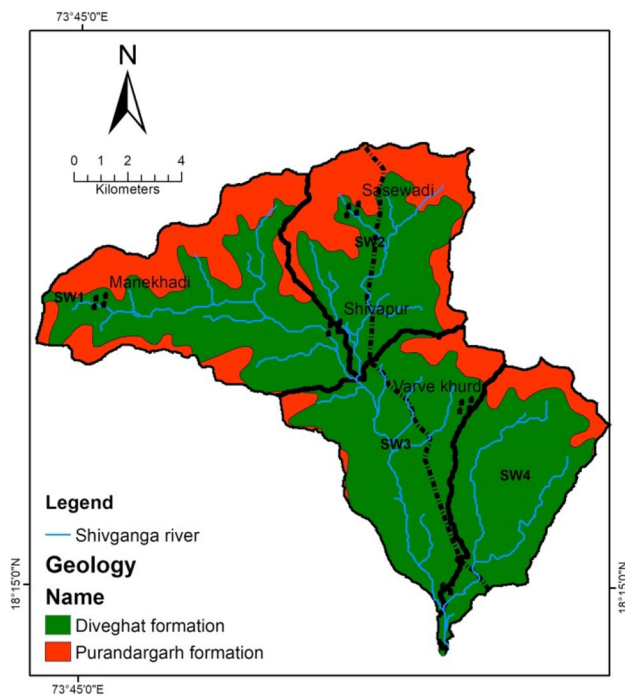


Fig. 7 Geology of Shivganga River basin

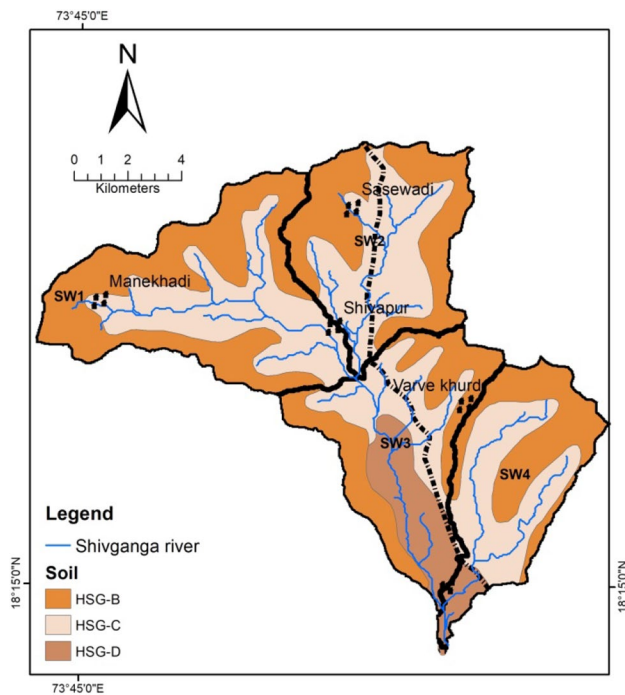


Fig. 8 Soil map of Shivganga River basin

4.7 Land use class

Land use is an important indicator of hydrogeological changes in water cycle as it affects the overland flow, evapotranspiration, infiltration and restores aquifer system [31]. LANDSAT ETM+ images have been used to prepare the spatial distribution of land use classes of the study area. The main land utilization class type comprises of agriculture, waste, forest/vegetation, built-up land and water bodies (Fig. 9). The land covered with forest/vegetation and agriculture land creates low overland flow [32], therefore considered as 'good' for GWR, and hence ranked 5. In contrast, in built-up land percolates less of water, hence considered as poor groundwater recharge potential sites, are given the rank 1.

4.8 Vadose zone

The vadose zone is the section of the rock material above the groundwater table. Hydrologically, this zone is crucial in proportionating the rainwater in subsurface infiltration and surface runoff. The soil water belt of vadose zone draws attention of agriculturists and soil scientists as the characteristics of this zone governs support to crops. The thickness of vadose zone increases along linear structures as well as reaches to valley floor in the study area as confirmed through the well inventory conducted during field work. The vadose zone thickness is categorized

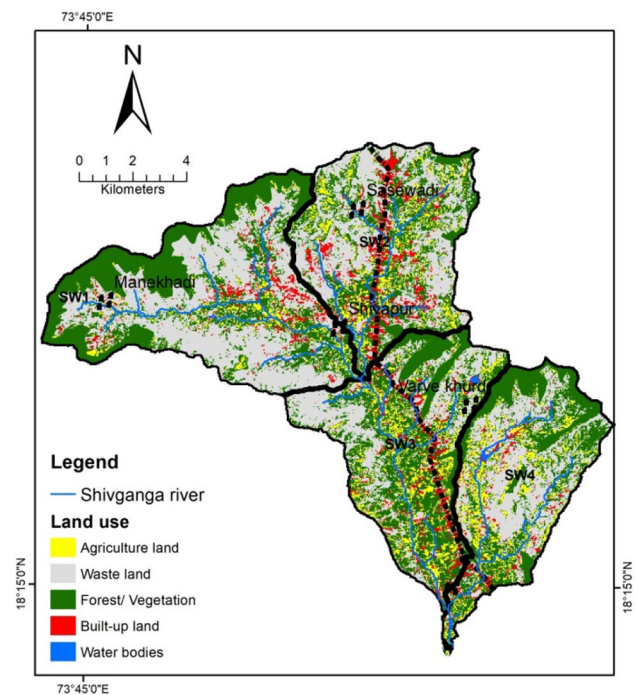


Fig. 9 Land use map

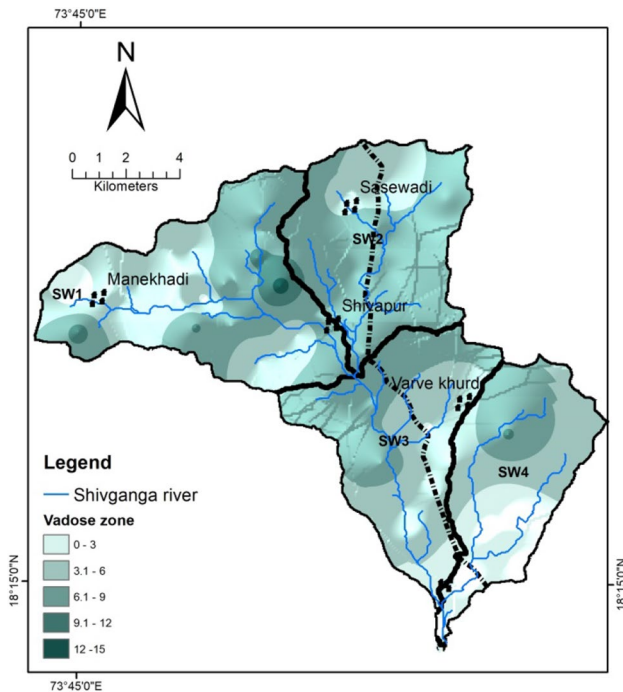


Fig. 10 Vadose zone map

into 0–3, 3–6, 6–9, 9–12 and > 12 m below the ground (Fig. 10). The vadose zone thickness 0–3 shows less potential for groundwater recharge which is given the rank 1 and > 12 m below the ground is having high potential of recharge which is assigned the rank 5.

5 Generation of pair-wise comparison matrices through AHP

Multi-criteria analysis technique such as AHP is used to define the weightage of thematic layer to remove the biasness in the resultant map. The AHP technique provides the comparative assessment between the parametric layers using pair-wise matrix that is further used for deriving the consistency of the assumption. The relative importance of parameter within themselves is given by referring the scale

Table 1 Saaty’s 1–9 scale of relative importance

Scale	1	2	3	4	5	6	7	8	9
Importance	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	Very strong	Very, very strong	Extreme

Table 2 Different RI values (Saaty 2008)

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.46

of 1–9 digits, where the 1 value is having equal importance for both comparative parameters while the 9 is having extreme important of one parameter over other (Table 1).

The random index (RI) value is a function of the number parameter (n) taken into consideration for comparison matrix. The random index values are given in table below (Table 2).

The last step in AHP procedure is to find consistency of resultant weight as well as the reliability of assumption. The consistency ratio is consistency index divided by random index value.

Based on AHP analysis for groundwater recharge zone identification, the CR value got is 0.097, which is below 0.10, i.e. 10%, so the weightages assigned to themes are accepted. The AHP shows that the rainfall (20.34%) is having highest weight, followed by the vadose zone, while the drainage density is having lowest weight (2.97%) as shown in Table 3. These weights were further used for identification of groundwater recharge potential areas as a final output map using weighted overlay analysis in GIS environment.

6 Weighted overlay analysis for recharge zone identification

The weights obtained using AHP were assigned to the thematic layer, while the ranks were given to the feature class of each thematic layer (Table 4).

The high recharge potential zone represented mainly plateau weathered geomorphology, agriculture as major land use, sandy clay type of soil with 9–15 m vadose zone thickness having slope less than 5%, hence offering higher resident time to rainwater for infiltration and increased the recharge to aquifer. The moderate recharge potential zone occurs in area having moderate slope, moderately dissected plateau with fallow/wasteland having loamy clay soil type showing mainly vadose zone thickness between 6 and 12 m (Fig. 11).

The low recharge is associated with the upstream part occupied by Diveghat formation having moderate to high drainage density with wasteland with sparse vegetation

Table 3 Pairwise comparison matrix and final weights obtained for thematic layer

Parameter	Geomorphology	Geology	LULC	DD	Soil	Vadose zone	Slope	Rainfall	% weight
Geomorphology	1.000	0.500	0.333	5.000	5.000	0.500	1.000	0.143	11.14
Geology	2.000	1.000	0.250	4.000	1.000	0.500	0.500	3.000	12.52
LULC	3.000	4.000	1.000	5.000	2.000	0.333	3.000	0.250	16.59
Drainage density	0.200	0.250	0.200	1.000	0.333	0.250	0.200	0.333	2.97
Soil	0.200	1.000	0.500	3.000	1.000	0.333	2.000	1.000	8.54
Vadose zone	2.000	0.500	3.000	4.000	3.000	1.000	3.000	2.000	19.33
Slope	1.000	2.000	0.333	5.000	0.500	0.333	1.000	0.200	8.56
Rainfall	7.000	0.330	4.000	3.000	1.000	0.500	5.000	1.000	20.34

Table 4 Detailed weights and relative weights of various thematic layers

Parameter	Categories	Rank	AHP % weights	Final AHP weight
Geology	Diveghat formation	3	12.52	12.52 × 3 = 37.65
	Purandargarh formation	2		12.52
Geomorphology	Butte	1	11.14	11.14
	Escarpment	1		11.14
	Mesa	1		11.14
	Plateau highly dissected	1		11.14
	Plateau moderately dissected	3		33.42
	Plateau shallow weathered	4		44.56
	Plateau slightly dissected	2		22.28
	Plateau weathered	5		55.70
Land use/land cover	Wasteland	2	16.59	33.18
	Built-up land	1		16.59
	Vegetation/forest	3		49.77
	Agriculture land	5		82.95
	Water bodies	4		66.36
Drainage density	Very high	1	2.97	2.97
	High	1		2.97
	Moderate	2		5.94
	Low	3		8.91
	Very low	4		11.88
Soil	HSG-B	4	8.54	34.16
	HSG-C	2		17.08
	HSG-D	1		8.54
Vadose zone (m)	0.0–3.0	1	19.33	19.33
	3.1–6.0	2		38.66
	6.1–9.0	3		57.99
	9.1–12.0	4		77.32
	> 12	5		96.65
Slope	0–5%	5	8.56	42.80
	5–10%	4		34.24
	10–15%	3		25.68
	15–20%	2		17.12
	> 20%	1		8.56
Rainfall	< 900	1	20.34	20.34
	900–1000	2		40.68
	1000–1100 mm	3		61.02
	> 1100 mm	4		81.36

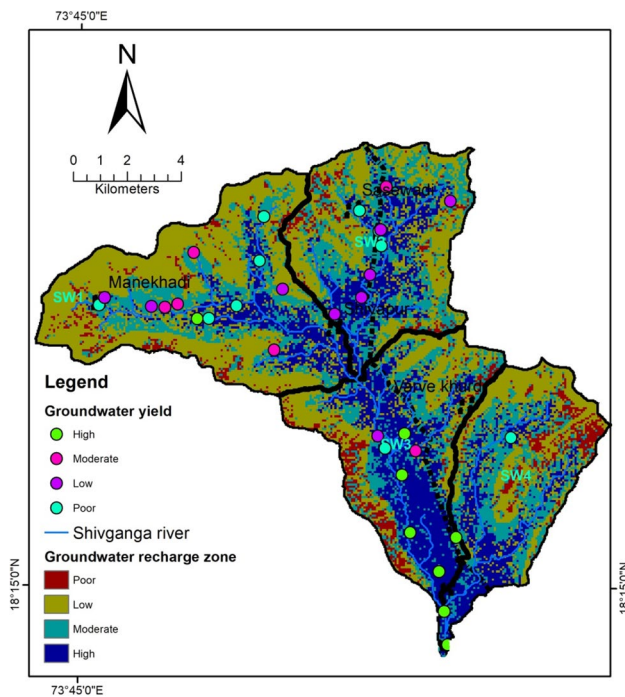


Fig. 11 Groundwater recharge potential zone map of study area

resulting into less resident time of water over the surface. The poor recharge potential zone shows basaltic flows mainly from Purandargarh formation with very high drainage density and steep slopes covering mesa and buttes. The poor recharge potential area mainly has the barren land with very less developed vadose zone, i.e. up to 4 m.

Table 5 Estimation of subsurface recharge capacity

WL	Area (km ²)	Depth to water level (post-monsoon) below cut-off level (m)	Volume of saturated zone (M m ³)	Average specific yield	Total recharge potential as volume of water (M m ³)
3–6	14.64	1.5	21.96	0.02	0.44
6–9	134.81	4.5	606.63	0.02	12.14
9–12	22.71	7.5	170.30	0.02	3.41
12–15	4.77	12	57.20	0.02	1.15
	176.92				17.12

Table 6 Availability of surplus water

Sub-watershed	Area Sq. km	Monsoon rainfall	Coefficient (K)	Runoff (Q=rainfall × coefficient) (mm)	Volume = (area × runoff) (M m ³)	30% of the total runoff (M m ³)
SW1	55.51	1100	0.700	770.00	42.74	12.82
SW2	41.87	1000	0.657	657.00	27.51	8.25
SW3	41.15	960	0.685	616.50	25.37	7.61
SW4	35.40	900	0.684	615.60	21.79	6.54
					117.41	35.22

7 Estimation of available storage space

The overall dimensions of vadose zone unsaturated are assessed, and actual volume of water essential to recharge the subsurface has been considered by multiplying with average specific yield of study area, i.e. 0.02% [33]. Typical formularies have been used in this method to estimate the volume of rainwater essential to recharge the unsaturated zone (Table 5). Apart from the recharge due to precipitation, in present study area approximately 17.12 M m³ recharge potential zone is available for artificial recharge.

The next step is the calculation of surface water availability by analysing the monsoonal precipitation pattern for groundwater recharge. As per the CGWB norms, 75% of water is recharged by the rainwater harvesting structures [34]. Thus, surface water requirement = storage space × 1.33 (A reciprocal of 75% efficiency). In the river basin, around 17.12 MCM is the available volume for artificial recharge (Table 5).

So, the water essential for artificial recharge = 17.12 × 1.33 = 22.77 MCM.

The normal average monsoon rainfall for last 50 years is 945 mm (IMD). The percentage of runoff to rainfall is given in Table 6. The total runoff generated from study area is about 117.41 MCM. The saturated area could store 117.41 MCM, whereas 30% of the total runoff (35.22 MCM) is considered as surplus monsoon runoff available for arresting in the form of artificial recharge.

The availability study shows that sub-watershed SW4 receives less rainfall (900 mm), hence less surplus water

for recharge, while SW2 in upstream part near Western Ghat region has ample rainfall with high slope having moderate water recharge capacity. The overall attempt of study would be useful for the watershed developer and planner for preparing watershed development plan.

8 Conclusions

The present study demonstrates a method to identify groundwater recharge potential zones for water conservation plans and artificial recharge to aquifers, in the semi-arid region watershed of Western India. The extension of water resource is done by estimating available recharge space for recharge and sub-watershed wise deficient or surplus surface water availability to conserve in artificial recharge structures. About 24.69% of the study area has been found to have high groundwater recharge potential, and 24.17% of the area is moderate for groundwater recharge. Remaining 44.34 and 6.80% of the total area come under, respectively, low and poor groundwater recharge potential zone. The surplus water availability was calculated based on vadose calculation according to CGWB method. In the watershed, around 17.12 MCM vadose region is present for artificial recharge. So, the water essential for artificial recharge = $17.12 \times 1.33 = 22.77$ MCM. The total runoff generated from Shivganga River basin is about 117.41 MCM. Area works out to 117.41 MCM, about 30% of the total runoff, i.e. 35.22 MCM is considered as surplus monsoon runoff available for artificial recharge.

It is clear from the ground investigations that the correctness of GWR potential zone map is genuinely accurate (82.85%) and provides valuable inputs for resource management. The higher accuracy is accredited by the use of MCDA analysis. Thus, the use of remote sensing, geospatial and MCDA technologies have demonstrated aptness while identifying the suitable areas for groundwater recharge over other conventional techniques.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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